Geophysical Monograph Number 1

Antarctica in the International Geophysical Year

Based on a Symposium on the Antarctic

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ANTARCTICA IN THE INTERNATIONAL GEOPHYSICAL YEAR

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Introduction

Considering our modern means of travel and communication, it is a matter of some wonder that so large a piece of our Earth planet as the unknown areas of Antarctica still remains unexplored. That the International Geophysical Year would focus unprecedented attention on Antarctica was a foregone conclusion.

As plans for our national participation in the co-ordinated geophysical exploration of Antarctica by eleven nations developed, it became increasingly evident that we should bring together available scientific knowledge of the Continent for background purposes in examining the major scientific problems awaiting us.

The invitation of the American Geophysical Union to have an Antarctic Symposium under its sponsorship on April 26 and 27, 1956, preceding its own Annual Meeting produced the needed action. The following persons were appointed to a special Symposium Committee and charged with the selection of both subjects and authors for the program: L. M. Gould, Chairman; Hugh Odishaw, Secretary; A. P. Crary; N. C. Gerson; J. W. Joyce; A. H. Shapley; Paul A. Siple; Waldo E. Smith; and Harry Wexler.

It is expected that this collection of papers will be a useful handbook for members of the IGY Antarctic staff. The papers, therefore, are not limited to our planned geophysical program but include other related areas of broad scientific interest.

All Antarctic programs must be viewed against their geographic settings. In the pocket of the back cover is the new American Geographical Society's map specially produced for the Antarctic IGY explorations.

To keep the volume as compact as practicable for its purpose, the following Symposium papers of less specific interest for such a handbook are omitted from the present monograph: "U. S. Navy Hydrographic Office Contributions to Our Knowledge of Antarctica" by Captain J. B. Cochran, U. S. Navy, and "Highlights of Antarctic Exploration" by Laurence M. Gould.

The special Thursday evening addresses by Admirals Richard E. Byrd and George Dufek are likewise omitted. Admiral Byrd dealt with the broad aspects of Antarctic interests beyond the IGY program and explained his responsibilities as Officer in Charge of Antarctic Programs for the Department of Defense. Admiral Dufek, Commanding Officer of Task Force 43, gave an illuminating account of Operation Deepfreeze No. 1, illustrated with motion pictures.

My thanks go to all members of the Symposium Committee for the successful outcome of their work. But I would like to add a special word of appreciation to Waldo Smith, not only for his help in formulating the program and in carrying it out, but likewise for his patience and for his skill in the supervision of the final editing of the papers herewith presented.

LAURENCE M. GOULD

Northfield, Minnesota
July 17, 1956

The International Geophysical Year Program of the United States

JOSEPH KAPLAN

Abstract—A brief description of the origin and development of the International Geophysical Year program is given. Some of the international aspects of scientific cooperation under the program are discussed with illustrative examples of how such cooperation enhances the value of certain selected experiments. United States contribution to the planning and execution of some joint undertakings is described in more detail, and special reference is made to World Archives and Data Centers which will serve to accumulate source material and make it accessible to scientists of all participating nations.

The story of the IGY goes back some six years when various scientists informally discussed how man could appreciably increase his knowledge of his physical environment. Mindful of the value of the limited Polar Year studies (1882–1883, 1932–1933) geophysicists concluded that a world-wide effort in some twelve fields of geophysics afforded the greatest promise of major advances. These views were discussed, again informally, at several international meetings — in particular, at the meetings of the International Union of Geodesy and Geophysics and the International Scientific Radio Union. These unions endorsed the proposed effort and recommended that the International Council of Scientific Unions (ICSU) undertake the task of international planning. The ICSU was the logical organization for this activity, inasmuch as it embraces all the scientific unions. Accordingly, the ICSU established a special committee for the international development of the IGY program, the Comité Spécial de l'Année Géophysique Internationale (CSAGI). The CSAGI then called upon the appropriate bodies in various countries for the planning of national programs. The national committees thereby created have met on several occasions in order to integrate and coordinate the separate programs into a truly cooperative, world-wide effort.

In the United States, the National Academy of Sciences, as the adhering body of the U. S. scientists to ICSU, established the U. S. National Committee for the IGY; and this Committee, composed of many of the Nation's leading geophysicists, has responsibility for planning, directing and executing the U. S. program. In this, the USNC-IGY is aided by its technical panels and their consultants, and by counterpart panels in the Department of Defense. In addition to the technical panels, the USNC-IGY has established four regional committees. These are the Antarctic, Arctic, Continental, and Equatorial Committees.

Solar activity—The period chosen for this major international effort was selected to coincide with a period of maximum solar activity. This will enable especially coordinated and intensified world efforts to be planned on such occasions as expected intervals of unusual magnetic, ionospheric, or auroral activity; on days of solar eclipses and unusual meteor showers. Special cooperative efforts will be made during these intervals to record the many phenomena which react so remarkably to the complex activities of the Sun.

Solar variations affect the weather in as yet undetermined ways. The very existence of the ionosphere and its complex variations which so profoundly affect radio communications depends on solar energy. The aurora and airglow are complex and fascinating manifestations of solar-terrestrial interactions. Variations in the Earth's magnetism and even in the cosmic rays that come into our atmosphere depend on the way in which the sun and its complex of emissions behave.

It is natural therefore that a broad-gage program to study solar activity would be one of the components of the overall IGY effort. Solar radiation will be observed in the visible, the ultraviolet, x-rays, and at radio frequencies. Solar flares will be studied and correlated with changes in cosmic rays, ionosphere and auroral distrubances, and geomagnetic phenomena. Sunspots, solar magnetic fields, line profiles of flares, absolute intensities of corona, and all other solar phenomena will be systematically observed and rapidly coordinated with the observing programs of the solar observatories of the world.

Meteorology—Of all the geophysical fields the one closest to man's everyday experiences and having the most devastating effects at times is meteorology. The IGY program in solar activity, geomagnetism, airglow, aurora, and ionospheric physics, by giving us added knowledge about the Sun and the high atmosphere, may also affect even our abilities to understand and forecast the weather. The solution of problems in one field with the aid of information derived from the other areas studied during the IGY is a general important characteristic of the entire complex and interrelated plan.

By establishing new aerological stations, and by working cooperatively with South American stations, it will be possible to construct a pole-to-pole line of stations roughly along the 80°W meridian. This line, together with similar lines established by other countries, will permit a much better delineation of the global transport of the various meteorological elements as a necessary step towards a better understanding of the atmospheric general circulation. In addition to this interesting system of pole-to-pole lines of stations, there are the seven United States meteorological stations which will be part of an international meteorological network on the Antarctic continent and adjacent territories, the first such network ever to be set up.

Aurora and airglow—Although the aurora and airglow are distinct phenomena in the upper atmosphere, they are generally linked together since both aurora and airglow are optical phenomena, observed spectroscopically and visually. The aurora, in addition, may be observed by radar and one can thereby obtain a record of the ionization associated with aurora. This ionization may be a help or hindrance to radio aircraft navigation, so that the full understanding of the aurora has its practical side too. Similarly, studies of the airglow have given us much insight into chemical processes that are hard to produce in the laboratory. They have also told us about motions in the high atmosphere and have thereby contributed to a rapidly developing picture of the meteorology of the very high atmosphere.

The IGY auroral program of the United States has as one of its primary objectives the construction of synoptic maps showing the distribution of aurorae. Photographic and visual observations will be used and, in addition, radar observations will be made. These have advantages over the visual and photographic records since clouds and daylight do not affect them. Special plans have been made to correlate studies of aurorae in both polar regions, and these should be invaluable for a better understanding of the theories of the motions of charged particles in the Earth's magnetic field.

The application of radio astronomy to auroral studies is another feature of the IGY. The scintillation of radio stars will be observed through auroral disturbances. Extra-terrestrial radio-wave absorption in the auroral zone will be observed, and an attempt will be made to study radio noise associated with the aurora itself.

The United States program for the airglow is concerned mainly with a chain of stations at the longitude of the Americas. Each station will be equipped with a photoelectric photometer of the Roach type as modified by Manring. In addition to this longitude chain, a few stations at different longitudes and latitudes will observe variations between the two hemispheres.

Cosmic rays—The study of cosmic rays is among the newest of the fields in geophysics. Cosmic rays behave as if the Sun acts on nuclear particles as a great cyclotron, accelerating them to cosmic-ray energies. On entering the Earth's atmosphere, they are affected by the Earth's magnetism and interact with the atmosphere itself, producing the secondaries. During the IGY, it is expected that knowledge will be gained of the reasons for the large decreases of cosmic-ray intensity during some magnetic storms, fluctuations of cosmic-ray intensity near sunspot maximum, the world-wide variation of cosmic-ray intensity with the sunspot cycle, and sudden large increases of cosmic-ray ntensity within an hour or less after the beginning of solar flares or chromospheric eruptions. Observers working at a network of stations will utilize simultaneous balloon and rocket flights in different latitudes and longitudes during periods of increased solar activity. Here too, as in other ifields, the interaction between the various programs is strikingly demonstrated.

Ionospheric physics—Like the program in meteorology, the one in ionospheric physics is characterized by its immediate applicability — this time to the vast system of radio communications. Here too synoptic programs will be carried out as well as other special observations.

The vertical-incidence soundings, in which radio waves are reflected from the ionosphere back to the station of origin, will be supplemented by oblique-incidence, back-scatter probings which will make it possible to explore the area from 600 to 1200 miles around each station. In addition to the synoptic program, other special observations will be made, as for example, oblique-incidence D- and E-region forward-scatter measurements for an equatorial region, and possible confirmation of the existence of F-region forward-scatter at UHF over long equatorial paths.

As in meteorology, ionospheric physics has a problem in forecasting radio blackouts and other variations in radio transmission. Here too there are gaps which are of great interest to the United States, and these lie in the Arctic, South America, Antarctic, Equatorial Pacific, and North Atlantic, as well as elsewhere in the world. The IGY presents an unprecedented opportunity to carry out ionospheric programs in these areas in cooperation with other interested nations.

Geomagnetism—We have mentioned several times how interdependent are the various fields of geophysics. The rapid variations in the Earth's magnetism provide us with a remarkable example of such interdependence. Ionospheric disturbances and auroral displays are closely connected with these changes in the Earth's magnetic field. A geomagnetic storm frequently occurs simultaneously with a strong aurora and radio blackout, and the purpose of the IGY geomagnetic program is to yield facts about these rapid magnetic-field fluctuations. The main features of the magnetic disturbances are such as would be caused by electrical current systems which flow in the upper atmosphere and are measured in hundreds of thousands of amperes. It seems reasonable to believe that the winds and currents in the high atmosphere are caused by bursts of radiation of some sort from the sun, which may be charged particles, or ultraviolet light and x-rays, or both.

Latitude and longitude—The IGY program in latitude and longitude determinations is designed to make more precise determinations of these quantities than has ever been done in the past. It is expected that in the determination of the differential shifts between continents the values of the coordinates for each station will be determined with possible errors of only a few feet. A comparison of these values with others to be obtained in the future will enable scientists to determine by what amounts, if any, the continents are shifting with respect to each other.

In the related Moon-position program of the IGY, scientists will try to solve several special problems in astronomy, geophysics, physics, and geodesy concerning uniform time, the irregular rotation of the Earth, and the size and shape of the Earth.

Gravity and seismology—The IGY affords an unusual opportunity for extending in a significant way, man's knowledge of the Earth's gravimetric field, the placing of gravity data now available on a common ground, and ensuring that future gravimetric work will have the same standard of reference. Six research activities are contemplated, including pendulum measurements, gravimeter measurements, underwater gravimeter measurements, submarine pendulum gravity measurements, Earth-tide studies, and Antarctic gravimeter observations.

The seismic research program will furnish information of fundamental importance to our understanding of the sediment thickness and layering of the solid Earth and has practical implications which affect our knowledge about basic constituents of the Earth and of earthquake characteristics. Three major activities are contemplated, including seismic exploration of the crustal structure, earthquake and seismic studies in Antarctica.

Oceanography—The winds and weather of the world play across a surface that is approximately three-fourths water, and the currents of the oceans move constantly in a huge circulatory system that vitally affects the climates of the one-fourth of the Earth that is land. A study of motions of the deep currents in the sea, such as the vast exchange of polar water masses with those of warmer oceans, is a requisite of long-range weather forecasting. Changes of sea level and tidal phenomena provide information about currents and geomagnetic effects and give important indications of significant weather trends, such as periods of gradual warming up of the entire world.

The overall objective of the Island Observatories project of the United States Oceanography program is to obtain an understanding of sea-level changes of both short and long periods and their relationship to other phenomena in the ocean and the atmosphere.

Operation Deep Current, the other United States project, will involve a study of the deep circulation of the water moving northward from Antarctica into and along the bottom of the Atlantic and Pacific, and multiple-ship, detailed studies of the areas of convergence and divergence in the North Central Pacific and North Central Atlantic. Scientists on the ships will also make very important submarine geophysical profiles of the Eastern and Western Atlantic basins and in the Central and Eastern South Pacific.

Glaciology—One effect of the warming up of the entire Earth would be the gradual melting of the world's supply of frozen water, the great glaciers and polar ice caps; if continued over a long period of time, this would have tremendous effects on the economic and political events in the world: opening of presently ice-locked ports in the far north; submersion of important coastal cities and low-lying coastal lands; alterations in the distribution of vast arid and verdant areas.

Glaciers are found on all continents except Australia, and occur even in the tropics, at high altitude, in South America, Africa and New Guinea. About ten per cent of the Earth's land surface is now covered by ice. Glaciers are extremely sensitive to meteorological factors, and in their variations indicate climatic changes of the past which, in some instances, can be dated by geologists and botanists. The stratigraphy and thermal regimen of a glacier also reveal evidence of present and past climate. In turn, glaciers, particularly the two existing ice sheets in Greenland and Antarctica, exert an appreciable effect on the weather of the planet.

The study of the glaciers of the world, an assessment of their present status, and an examination of their delicate relationship with existing climate will occupy glaciologists during the IGY. The United States program will encompass detailed studies at points in the Northern Hemisphere and at stations in the Antarctic, as well as reconnaissance observations in the western United States, Alaska, and portions of the Arctic in cooperation with Denmark and Canada. Observations made at United States Antarctic stations and by traverse parties operating between stations and radiating outward from them will have as main objectives studies of the present condition of the Antarctic ice sheet with regard to nourishment, wastage, volume and extent, structure, thermal regimen, and variations.

Rockets and satellites—During the IGY three approaches to obtaining direct upper atmosphere data will be utilized: launching of large rockets from the ground, firing of smaller rockets from balloons and from airplanes, and launching of Earth satellites. A total of more than 600 rockets of different sorts will be launched by the United States for geophysical research purposes.

Rocket studies will provide critical direct data about the nature of the atmosphere. While radiosonde balloon measurements to provide direct weather data to altitudes of 100,000 feet and cosmic ray balloons have attained heights of 140,000 feet, most of our knowledge of the upper atmosphere depends on indirect observations from ground stations. The rocket and satellite programs are designed to cover significant cross-sections of the atmosphere. Rockoons and rockairs will collect data up to 60 miles. The Aerobee-Hi will probe to 200 miles. Earth satellites will gather scientific information between some 200 and 800 miles above the Earth.

Instruments carried aloft by the rockets and satellites will make many observations which cannot be made from the ground: detection and measurement of solar ultraviolet and x-radiations absorbed by the atmosphere at high altitudes; direct measurements of chemical and ion composition of the upper atmosphere; direct detection and measurement of auroral particles; detection and measurement of ionospheric current flows; measurement of the Earth's magnetic field at high altitudes; and observation of low-energy cosmic rays. The direct data obtained from these measurements provide a means of conversion of indirect data obtained at ground stations into equivalent direct data; these measurements include those of atmospheric structure (pressure, temperature, and density), winds, ionospheric charge densities, heights and intensities of airglow, and heights and intensities of auroral radiations.

Rocket information will especially benefit the fields of weather prediction and radio communications and will also have great value in other IGY studies of solar activity, cosmic rays, geomagnetism, and aurora and airglow.

One of the great disadvantages of the conventional rocket program is that the rocket does not stay at great heights long enough to permit certain important types of measurements to be made. That is why so much thought has been given to the project of artificial Earth satellites carrying equipment for sicentific measurements. A single successful flight of the satellite will provide more observing time in the very high atmosphere than has been provided by all of the ordinary rockets that have been fired.

The Antarctic Program—From the beginning, the Antarctic has played a very important part in plans for the IGY. There are a number of reasons why observations on the Antarctic continent have an exceptional value in geophysical studies. First of all, the IGY program will require coordinated observations from many difficult points on the surface of the Earth. Observation stations in the Antarctic are essential to a full coverage of geophysical phenomena in the Southern Hemisphere. In particular, the Pole Station will form the terminal link in pole-to-pole chains of sites running along three meridians: longitude 10°E (through Europe and Africa), 75°–80°W (through North and South America), and 140°E (through eastern Asia and Australia).

There are, of course, certain observations that can only be made in the polar regions. Proximity to the south magnetic pole permits important observations of geomagnetic phenomena, not possible elsewhere. Also, since the lines of force of the Earth's magnetic field are perpendicular to the surface of the Earth at the magnetic poles, more cosmic rays reach the Earth's surface there than anywhere else, permitting unique observations.

The aurorae, too, are polar phenomena. The United States stations in Antarctica, located near the edge of the southern auroral belt or within it, will be ideally located for observations of the

Aurora Australis. In these studies and in several other programs, coordinated observations at both poles will be necessary.

The Antarctic is obviously a primary source of data for the glaciologist, since it is the largest single repository of ice and snow on the surface of the Earth. Studies of successive layers of Antarctic ice can tell us much about the climatic history of the Earth and, more important, will reveal much about our changing climate and environment at the present time.

The Antarctic is believed by some to be a breeding place of the world's weather. The furious storms of the Antarctic winter are probably a major factor in determining the weather of the whole Southern Hemisphere, and their effects even appear to extend across the equator into the Northern Hemisphere. Observers at Antarctic stations will have an invaluable opportunity to study this weather in the making, to follow movements of the atmosphere, and to relate these to the weather in other and distant regions.

Finally, the absence of the Sun during the long polar night also has its effects on the ionosphere. Radiation from the Sun, specifically ultraviolet and x-radiation, breaks up the atoms and molecules in the upper atmosphere into electrons and positive ions. These electrically charged particles, in effect, make a mirror of the ionosphere, so that it reflects back radio signals. In the long Antarctic night, however, particularly at the South Pole itself, the Sun's radiation is absent, and this gives rise to the important question of the composition and characteristics of the ionosphere under those unique and interesting conditions.

The Antarctic program has grown rapidly since the Rome meeting in 1954. Eleven nations will operate thirty-seven stations. The special Antarctic Conference, held in July 1955 in Paris, and attended by representatives from eleven National Committees, constituted a historic meeting. Never before had such concentrated attention been paid to Antarctic science or to the continent itself. Among the many technical resolutions resulting from this Conference was the designation of the United States to establish and operate a 'Weather Central.' This Central was anticipated to function as a collection center during 1957–59 for weather information from all Antarctic stations, traverse parties, expedition ships, aircraft, whaling vessels, ocean islands, and stations in South America, Africa, Australia, and New Zealand. The IGY Weather Central will serve as an analysis center at which all features of the atmosphere will be analyzed and studied. For the first time in history, daily weather maps will be prepared for Antarctica. The Weather Central will issue weather advisories and forecasts to help in the planning and carrying out of operations on land and sea, and in the air. This is of particular importance to the success of both land and air operations.

The United States program is presently designed to obtain maximum information from a limited number of stations and with the most efficient use of available logistics support. Some seventy scientists will man the six research stations for two one-year periods. Studies in a number of geophysical fields will be made: aurora and airglow, cosmic rays, geomagnetism, glaciology, ionospheric physics, meteorology, seismology, and gravity measurements. In addition, a small but pioneering program of rocket exploration is scheduled to be carried out by means of rockoons from aboard an icebreaker off the coastal ice shelf.

It should be pointed out that the vast increase of effort in the Antarctic by the participating IGY nations offers a guarantee as to the success of this great endeavor. It does more than this, however. A far more significant study of the continent can now be undertaken, and the present complement of stations—30 pct above that earlier contemplated—provides a relatively fine network, vastly augmenting the value of the data. In this unprecedented program, the United States effort is not only of great interest to the United States directly, but it is one of the many efforts, all of which are interdependent if maximum results are to be obtained.

The Arctic program—It is the Arctic which has originally fostered the concept of strong international cooperation in geophysics now culminating in the International Geophysical Year. The previous coordinated attempts in geophysics—the Polar Years of 1882–83 and 1932–33—were devoted wholly to the Arctic, and even though the IGY of 1957–58 is global in scope, continued serious interest in the Arctic still remains. It is well for this interest to continue, for the Arctic yet holds many secrets in its geophysical treasure chest.

Both polar regions have a dominant influence over weather in their respective hemispheres. This control is especially evident in the Northern Hemisphere, where intense low pressure areas and their accompanying storminess and precipitation areas are usually formed on a frontal surface between polar air and a tropical maritime air mass. The effects of the cold air masses on local weather are well known even in subtropical regions where, for example, rain and turbulence may accompany the passage of a front over the Caribbean Islands. Whether arctic air masses affect weather in the Southern Hemisphere is unknown, but the reverse condition has been conjectured.

Since the center of gravity of the world's population lies in the Northern Hemisphere, the influence of the Arctic on many of man's daily activities is more evident here than in the corresponding case for the Southern Hemisphere. In addition to weather, radio-wave communications between North America and Eurasia are very much controlled by polar, or in this instance, auroral conditions.

Radio signals follow the great circle path; in traveling from Washington to London, Stockholm, or similar locations, the radio path skirts the auroral zone. During periods of aurorae or geomagnetic storminess, the polar ionosphere becomes violently 'inflamed'; instead of acting as a reflecting region for radio waves, it becomes a strong absorber of radio-wave energy. This condition, while somewhat minor during periods of sunspot minimum, becomes of great concern during solar maximum when radiotelephone and radioteletype circuits between North America and Europe are interrupted frequently for appreciable periods of time. The usual practice to avoid such disruptions is to reroute radio signals from North America to South America, thence to Africa, and finally northward into Europe.

Even aside from such topics of immediate concern, however, the Arctic is interesting in studying the long-term trends of the Earth. Recent estimates have indicated that by the turn of the century it is possible that the Arctic may become a navigable sea, at least during summer. The implications to North America in such an eventuality, both transportation-wise and economically, are tremendous.

Interest in the Arctic is considerable and extends through all geophysical disciplines. The network of stations on the continents is extensive and was planned to allow maximum effectiveness in studying the aurora, cosmic rays, the ionosphere and geomagnetism, as well as the hard Earth sciences themselves.

To meet further its global responsibilities in the IGY effort and to supplement the existing network of ice pack stations, the United States plans to implement two Drifting Stations in the Arctic Ocean basin, one located at 160°W, 78°N, and the other at 100°W, 85°N. The stations, moving with the Arctic Ocean ice pack, will prove important bastions for geophysics in vital areas from which rather little is known.

Because of their location, major emphasis on the Drifting Stations will be devoted towards a study of the climatological sciences—meteorology, glaciology, oceanography, and climatology. Studies of ice thickness, movement, cleavage, and age will allow better theories on the life cycle of the Arctic Ocean sea ice and its drift, both of value to future navigation. Investigation on the rate of accretion of ice may provide some inkling of the future climatic trends of the Earth. Meteorological information to be gained will fill large gaps in the daily weather map and will contribute not only towards a better understanding of the movement and metamorphosis of air masses, but also towards greater forecasting accuracy in middle latitudes. Oceanographic studies in the Arctic basin, including analyses of samples from the ocean floor, will assist in differentiating between rival theories regarding the character of the Arctic Ocean itself—whether it is a true ocean like the Atlantic, or of the nature of the sea, similar to the Mediterranean.

The size of each Drifting Station is planned to accommodate about fifteen men. Supply and logistics will be entirely through air support. The United States National Committee thoroughly appreciates the difficulties involved in landing heavy aircraft on the uncharted ice pack to support the small but invaluable US-IGY stations.

The planning and direction of this challenging program, as already pointed out, have been the responsibility of the National Academy of Sciences. In this task, the Academy has gathered together leading scientists of the Nation. Through their assistance, and that of many private and public institutions and agencies, a sound technical program has been developed. The execution of this program will require the continued collaboration of scientists and institutions throughout the country. The success of IGY depends heavily on the cooperation and participation of scientists and their institutions. By the same token, IGY also affords remarkable opportunities for personal and institutional participation and achievement.

U. S. National Committee for IGY, National Academy of Sciences, Washington 25, D. C.

Antarctic Research During the International Geophysical Year

H. Wexler

Abstract—During 1957 and 1958 a dozen nations will maintain 40 geophysical stations in Antarctica. Thus, this Continent, the fifth largest in the world, will be subjected to concentrated, coordinated geophysical exploration to a degree not dreamed possible a few years ago. For the first time, geophysical stations will be established for an extended period of time well away from the coasts, deep in the interior of the Continent. Scientists from the participating nations will cooperate in examining the composition, structure, winds, temperatures, and electrical properties of an atmosphere cut off from sunlight for many months. The thickness of the ice will be surveyed for indications of changes in volume to determine if Antarctic climate is changing. The break-up and movement of the peripheral ice will be studied as a function of wind and ocean currents. The aurora australis will be studied and compared with its Northern Hemisphere counterpart. Intensive measurements will be made of geomagnetism, cosmic rays, airglow, and the ionosphere in an attempt to throw light on the physics of the high atmosphere.

Ninety-five years ago this April, in the year 1861, when Washington was in turmoil about the coming Civil War, a letter from the U. S. Navy Department was delivered to Lord Lyons, the British Ambassador. A few months later in London the letter was sent from the Under Secretary of State for Foreign Affairs to the Lords Commissioners of the Admiralty, who then transmitted it to the British Association for the Advancement of Science to be read at the annual meeting in Manchester.

The letter, written by Matthew Fontaine *Maury* [1861], Commander, United States Navy, just before he resigned his commission to join the Confederacy, proposed international cooperation in the scientific exploration of the Antarctic. It pointed out how all the principal maritime nations of the world were cooperating in gathering and exchanging information on winds and ocean currents, and expressed the hope that this same spirit would "... unbar the Gates of the South." More of Maury's words bear repeating here not far from the spot where they were written 95 years ago:

> "If, in pleading the cause of Antarctic exploration, I be required to answer first the question of *cui bono?* which is so apt to be put, I reply, it is enough for me, when contemplating the vast extent of that unknown region, to know that it is a part of the surface of our planet, and to remember that *the Earth was made for man*; that all knowledge is profitable; that no discoveries have conferred more honour and glory upon the age in which they were made, or been more beneficial to the world, than geographical discoveries, and that never were nations so well prepared to undertake Antarctic exploration as are those that I now solicit."

After mentioning the previous contributions to knowledge of the Antarctic by men of many nations, Maury outlined the practical steps required:

> "The first step, I submit, should be to send a steamer down from Australia to search for one or more ports or places where the exploring vessels that are to follow may find shelter, and whence they might despatch boat- or land- or ice-parties, according to circumstances. This reconnaissance alone would occupy one season.
>
> "The next season, vessels suitably equipped for two or three years might be sent to take up their position, where at the return of summer they might be visited from Melbourne again, and arrangements made for the next season.
>
> "For many seasons this exploration should be a joint one among the nations that are most concerned in maritime pursuits. The advantages are manifold: each one of the cooperating powers, instead of equipping a squadron at its own expense, would only furnish one or two steamers; and these should not be large, nor should their cost be extravagant. Thus the expenses of a thorough Antarctic exploration, like those for carrying on the 'Wind and Current Charts,' may be so subdivided among the nations concerned as literally to be 'almost nothing.' It would also be attended by this further and great advantage—such an expedition could have several centres of exploration. The officers and men under each flag would naturally be incited by the most zealous and active emulation. They would strive so much the more earnestly not to be outdone in pushing on the glorious conquest.
>
> "Now the question is, what mode of procedure is best calculated successfully to bring this subject to the notice of the proper authorities in your country?"

Similar letters went to the other principal maritime countries, but there is no record to show that anything was done about Maury's proposal. Indeed, it appears to have lain forgotten until 43 years later, when Henryk Arctowski, the first meteorologist who wintered in the Antarctic—

on the *Belgica* in 1897–99—referred to it in Washington at the 8th International Geographic Congress, September 1904, in pleading anew the cause of international cooperation in the scientific exploration of the Antarctic.

It was not until 45 years later, in 1949, when at the initiation of the famed Swedish geophysicist, H. W. Ahlmann, that the Norwegians, British, and Swedes pooled their resources to form the first truly international expedition to the Antarctic, which led to the establishment of the station at Maudheim in Queen Maud Land.

The next year, 1950, in a suburb of Washington, the idea for an International Geophysical Year in 1957–58 germinated and spread to other countries. Four years later, in January of 1954, the United States National Committee for the IGY, at its fourth meeting in Washington, endorsed a proposal by its meteorological rapporteur that the United States establish three IGY stations in Antarctica—Little America and, for the first time deep in the interior of the Continent, stations at 80°S, 120°W, and the geographic South Pole. This proposal was presented at the CSAGI meeting in Rome in October 1954 and five nations among those present agreed to establish 12 stations on the Antarctic continent. At latest count this has grown to ten nations planning to establish 37 stations on the Continent, four of them deep in the interior.

So, today, in Washington, in fulfillment of Maury's dream, we meet to summarize past knowledge of Antarctic geophysics and to discuss plans for further investigations in the various scientific disciplines which will be carried out in Antarctica in cooperation with other nations. The 'mode of procedure' that Maury asked for nearly a century ago is now in existence and is working harmoniously and efficiently through the various international and national scientific bodies and conferences engaged in the IGY.

Why are we interested in the Antarctic from a geophysical point-of-view? First, as Maury said, it is part of our planet and a largely unknown part, too. Second, it is the largest repository of ice in the world, containing 86 pct of all the world's glacial ice. Third, it is the world's most efficient cold-air factory, far more so than the Arctic. It also contains the Pole or the hub of the atmospheric circulation in the Southern Hemisphere. Fourth, its melting ice creates vast amounts of cold water, which sink to the bottom of the ocean, and, as the Antarctic Bottom Current moves across the equator into the Northern Hemisphere. Fifth, it enables study to be made of the aurora australis and comparisons with the aurora borealis. Sixth, it contains the South Magnetic Pole. Seventh, it presents a stable platform for the study of the thermal and electrical properties of an atmosphere cut off from sunlight for many months.

There are many other reasons why Antarctica is a geophysicist's paradise, but I shall not go into detail. Instead, I will mention some scientific aspects of several of the principal expeditions of the past and then present some over-all features of the U.S. program.

Although Antarctica was discovered in 1820, no one landed on the continent till 1895. The first wintering in the true Antarctic was done by the *Belgica* in 1897–99, south of Peter I Island. *Arctowski* [1904, U. S. Navy Department, 1951], meteorologist of this expedition, published dozens of papers in Antarctic meteorology, aurora, geology, atmospheric optics, glaciology, floating ice, oceanography, and marine sediments. He is in his 85th year, lives in Florida, and I have recently received a letter from him, which outlined his work and lists unsolved problems in Antarctic bathymetry, glaciation, and geology.

The first scientific party to winter on the Antarctic mainland itself, Cape Adare, was the British Expedition on the *Southern Cross* led by Borchgrevink, which explored the Ross Sea in 1898–1900.

The first extensive exploration and scientific investigation on the Antarctic continent itself was done by the British National Antarctic Expedition, under leadership of Scott, in 1901–04. A 380 mile southward penetration was made on the Ross Shelf Ice as well as a 300 mile westward trip onto the 9000 ft Victoria Land plateau. Another outstanding feature of this expedition was the advance preparation of a several hundred page *Antarctic Manual* for use of expeditionary members, with chapters written by such illustrious men of science as Kelvin (atmospheric electricity), Arthur Schuster (aurora), Scott (Antarctic climate), Buchanan (chemical and physical notes), and G. H. Darwin (tidal observations). The many papers written in these fields after the expedition returned occupy several volumes published by the Royal Society.

Von Drygalski, 1901–03, on the German ship *Gauss* took many valuable scientific measurements in the pack-ice 50 miles off shore and these latter formed the basis for scores of scientific papers.

The Swedish Expedition of 1901–03, under Nordenskjold, took valuable observations near Ross Island, and dozens of papers were published.

The British Expedition under Schackleton, 1907–09, explored Ross Island, penetrated to the South Magnetic Pole and to 97 miles of the South Pole, taking numerous scientific observations, with the results published in a series of volumes.

The Second Scott Expedition of 1910–1913 established two bases, Cape Evans and Cape Adare. Expedition members took observations in meteorology, geomagnetism, atmospheric electricity, and geology. Simultaneous observations in meteorology were taken for the first time on the Continent. The first upper air soundings and weather charts in Antarctica were made by Sir George Simpson, meteorologist with the Expedition, who, in writing up his discussion of the meteorological and electrical observations, set a pattern for polar scientific reports which was followed by Sverdrup of the *Maud* Expedition and others. Sir George has sent the following message:

> "As a member of Captain Scott's Expedition to the Antarctic in 1910–12 I welcome this opportunity of greeting those who will visit polar regions in connection with the International Geophysical Year.
>
> "I cannot help contrasting the conditions of scientific work in polar regions then with those of today. In 1910 only wooden ships were used to penetrate ice-covered seas; the only energy available for transport over snow-covered land was the animal power of men, dogs and ponies; there was no communication with the outside world, and scurvy was the chief, almost the only, danger to health.
>
> "Now iron ships have replaced wooden; motors and aeroplanes are used for transport; scurvy has been completely eliminated, and explorers at either Pole can communicate daily with their families and friends in the home country.
>
> "The great Antarctic Expeditions of 1910–15 may be truly said to have brought one Age of Polar Exploration to an end, and now a new one is being introduced with problems and means never dreamt of in the Old Age.
>
> "But one thing has not changed, and that is the urge to learn the secrets of nature in all their forms and in every part of the universe. I wish the pioneers of the New Age the comradeship, the self-sacrifice and the devotion to science that I experienced in the Old Age: their success will then be certain and an increase in knowledge their reward."

The Mawson Expedition of 1911–14 took numerous scientific observations on the George V Coast and adjacent areas.

Following the first use of an airplane in Antarctica by Sir Hubert Wilkins, Admiral Byrd's First Expedition to Antarctica in 1928–30 used it extensively as an exploratory and scientific aid. Observations in glaciology, geology, meteorology, cosmic rays, ionosphere and radio propagation formed the basis of valuable scientific papers by such familiar figures now involved in present IGY planning as Gould and Berkner.

The Second Byrd Expedition of 1933–35 carried out scientific programs in meteorology, ionosphere, meteors, cosmic rays. Thickness of the Ross Ice Shelf was determined for the first time by seismic methods. The Bolling Advance Base, occupied by Admiral Byrd, was the first long-term station established well away from the coast.

The 1939–41 Expedition, supported by the U. S. Antarctic Service of the Department of Interior established two bases, one at Little America and the other on Palmer Peninsula. At Little America, Court made the most extensive series of upper atmosphere soundings in Antarctica; this was done over a nine-months period and revealed unusual features aloft discussed in another paper of this Symposium.

In 1947–48, Finn Ronne's expedition wintered over at Marguerite Bay, Palmer Peninsula and performed valuable research and exploration there and in the adjacent Weddell Sea.

The Norwegian-British-Swedish Expedition of 1949–52 enriched the Antarctic geophysical literature with valuable papers on meteorology, glaciology, solar radiation, and energy balance.

In Figure 1 the proposed IGY station locations, are shown on a map of Antarctica [see also U. S. National Committee for IGY, 1956]. The five U. S. stations, identified by stars, will cover one-half of the continent from the Weddell Sea westward to Marie Byrd Land, Little America, the Ross Sea, and the Knox Coast. Another station, Cape Adare, will be operated jointly by New Zealand and the United States. New Zealand will also have a station at McMurdo Sound at which most of the scientific measurements in that area will be taken. The United States will have a nearby air support facility to furnish air lift to and from Antarctica and aid in the establishment of the United States scientific station at the geographic South Pole. A small supplementary scientific program will be established at this facility.

Stations proposed by other nations are also shown. The USSR plans three stations, one at the Knox Coast to the west of the United States base, and two inland—one at the South Geomagnetic Pole and the third in the center of the continent, known as the Pole of Inaccessibility. A few months ago our planes flew over this territory and found a high snowy plateau, ranging from 10,000 feet to 13,000 feet in altitude.

The French station at Adelie Land, originally established in 1949–53, will be reoccupied during

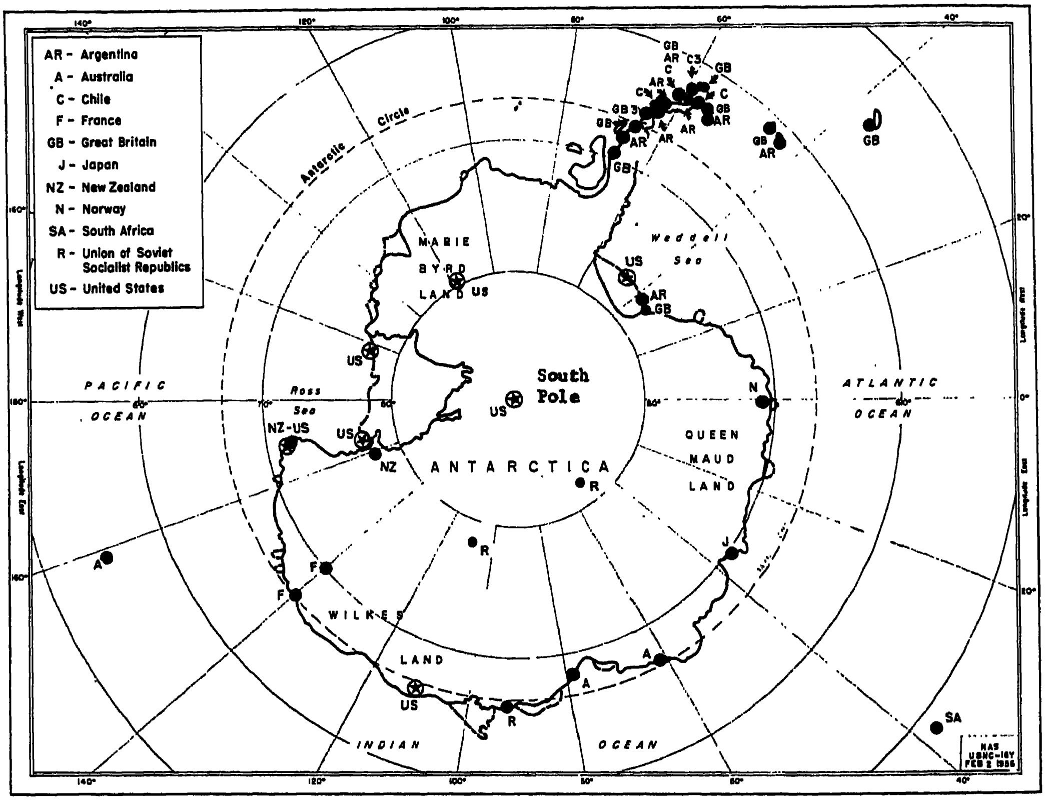

FIG. 1 – Planned Antarctic stations

the IGY and will have a satellite station a few hundred miles inland, near the South Magnetic Pole. The Australians have had their Mawson station established on the coast of Enderby Land for two years and have recently made a reconnaissance to open up a new station at Vestfold Hills, a few hundred miles to the east.

The Japanese will enter actively into Antarctic work for the first time since 1912 when Choku Shirase discovered Kainan and Okuma Bays. Kainan Bay is now used as a harbor to supply the present United States Little America V station, located three miles to the south. The Japanese have volunteered to fill an important gap on the Prince Harald Coast between Mawson and the Norwegian Station to be located near Maudheim, site of the joint Norwegian-British-Swedish Expedition of 1949–52. On the Weddell Sea the Argentines, British and Americans will each have a station. The U. S. will attempt to penetrate far west, to the foot of the Palmer Peninsula, if ice conditions permit.

The Palmer Peninsula already has a dense network of stations, established by Argentina, Chile and Great Britain, but most of these emphasize surface meteorological observations.

In Figure 2 is shown the distribution of the U. S. and joint New Zealand-U. S. stations plus the proposed traverses to be made during the summer seasons by the field parties which will take observations in glaciology, seismology, gravity and meteorology.

In Table 1 is shown the distribution of scientific program among the United States stations. Similar programs differing perhaps in emphasis will be carried out at most of the stations of other countries.

It is planned to release about 40 rockoons (balloon-borne rockets fired at 25 km and reaching to 100 km) from an ice-breaker to observe cosmic-ray intensity, air luminescence due to aurora, geomagnetism, and atmospheric electrical currents. These rocket launchings will be coordinated with similar launchings in the Northern Hemisphere. In Table 2 is shown the distribution of U. S. scientific personnel according to station and discipline. In summer, 18 additional scientific persons will be added.

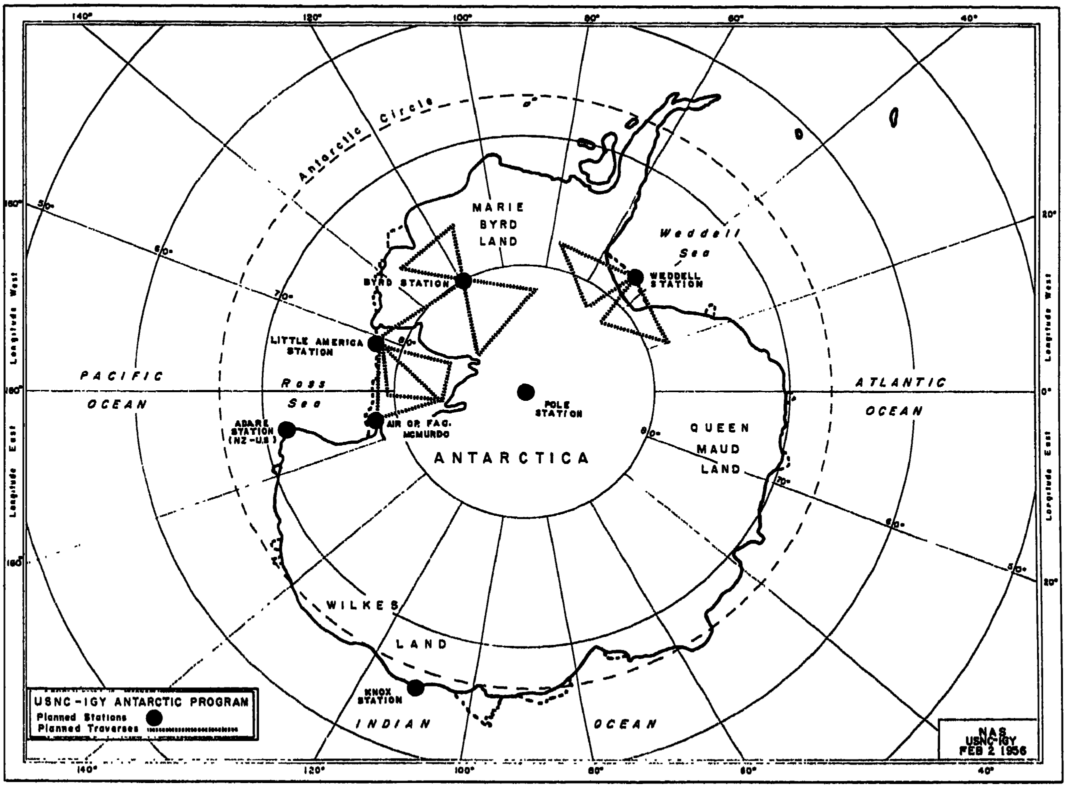

FIG. 2 – Planned United States Antarctic stations

TABLE 1 – *Scientific program distribution*

Station	Activity (see key below)									
Little America	A	C	Gm	Gl	..	I	M	..	..	S
Byrd	A	..	Gm	Gl	..	I	M	..	..	S
Pole	A	..	Gm	Gl	..	I	M	..	..	S
Weddell	A	..	Gm	Gl	..	I	M	..	..	..
Knox	A	..	Gm	Gl	..	I	M	..	..	S
Adare	A	..	Gm	..	..	I	M	..	..	S
Williams Facility	..	..	..	..	Gr[a]	..	M	..	..	..
Traverses	..	..	..	Gl	Gr	..	M	..	..	S
Ships	..	C	..	..	..	..	M	O	R	..

Key
A —Aurora & Airglow
C —Cosmic Rays
Gm—Geomagnetism
Gl —Glaciology
Gr —Gravity Measurements
I —Ionospheric Physics
M—Meteorology
O —Oceanography
R —Rocketry
S —Seismology

[a] Summer 1956–57.

TABLE – 2 *Summary of scientific personnel*

Activity	LAS	Byrd	Pole	Weddell	Knox	Adare	Williams	Total
Administrative	3	1	1	1	1	..	..	7
Aurora and Airglow	1	1	1	1	1	1*	..	6
Cosmic Rays	1	..	..	..	..	..	..	1
Geomagnetism	1	1	..	1	1	½*	..	4½
Glaciology	6	2	1	2	3	..	..	14
Gravity	1	1	..	1	..	..	..	3
Ionosphere	2	1	1	1	1	1*	..	7
Meteorology	12	4	4	5	5	4	4	38
Seismology	3	2	0	2	1	½*	..	8½
Other	2	2	1	..	1	..	..	6
Total	32	15	9	14	14	7	4	95

* New Zealand personnel

Meteorology has most personnel, not only because of the demands of an intensive observing program, but because the United States has been given the responsibility of running the IGY Antarctic Weather Central, where meteorological observations will be collected and re-broadcasted internationally. The weather analyses and forecasts prepared at the Weather Central will be issued regularly for the use of all countries operating in Antarctica.

A small research program in physiology and psychology will be carried out by station medical personnel.

Although the preceding tables might suggest rigid compartmentalization of the various disciplines, this is not the case. One of the features of the present IGY, as compared with its predecessors of 1882–83 and 1932–33, is the realization that practically all the geophysical sciences are interrelated. For example, the location of the South Magnetic Pole in Antarctica permits less energetic cosmic-ray primaries to penetrate deep into the atmosphere. But also the belt of unusually low barometric pressure found at the coast means there is three to five per cent less atmospheric mass than elsewhere; this, combined with the low temperature of the air column above, so contracts the atmosphere vertically that various secondary radiations emanating from collisions of cosmic-ray primaries with air molecules can reach the Earth's surface in greater intensity. The height of the 100 mb surface at Maudheim in winter is 2000 feet less than at Thule and 5000 feet less than that at Washington.

A second example is the inter-relation of meteorology, seismology, glaciology, geology, and botany in determining whether the inland ice is receding or growing, and in establishing a record of past variations in climate.

A third example is a solar disturbance such as occurred April 26, 1956. This affected the ionosphere, causing an historic magnetic storm, radio-blackouts, aurora, and probably an increase in cosmic-ray intensity. The controversial question as to whether solar disturbances can cause significant changes in sea-level meteorology will probably be resolved by the more numerous and unusual observations collected during the IGY.

I am confident that many similar across-the-field relationships, as yet unsuspected, will emerge as the IGY observations are collected and analyzed, and, just as important, when the working scientists of many different fields are thrown into such close contact with each other that they just can not help but absorb some knowledge about the other fellow's field.

I come now to the end of this brief synopsis of Antarctic geophysical research—both past and future. The planning phase, combining the labor of dozens of scientists and logistics experts, is nearing completion; the field phase will begin in November when the main United States scientific party of 95 volunteers departs for Antarctica. The placing of these highly trained men safely in the designated places at the proper time, together with their sensitive equipment, is a task which the Department of Defense, particularly the Navy, has assumed whole-heartedly and whose personnel deserve the gratitude of all of us connected with the IGY program.

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Antarctic Geography

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Abstract—The challenging task of unveiling the Antarctic Continent has been greatly aided by the advent of new technologies during the past quarter century. The scientific and material developments which contributed most to the increased capability for polar exploration have been in the fields of transportation, communications, and aerial photo surveying. Advances in sciences and technologies in such fields as atomic energy power and heat, food technology, environmental protection, and shelter improvement have tended to make the concept of protracted occupation of the Continent more tenable for the future. Although currently two-fifths of this five million square-mile continent is yet to be seen for the first time, there is every likelihood that before the IGY draws to a close most of the major geographic discoveries will have been made. Concepts of the Antarctic Continent have gradually improved.

The Continent appears to be a 'siamese-like' juncture of two large land masses. The portion lying mostly in the western hemisphere, conveniently designated West Antarctica, is only about half as large as East Antarctica. The latter is believed to be a massive Precambrian shield superimposed by a great dome of snow and ice, and toward its center reaching in excess of 13,000 feet elevation. The smaller West Antarctica is more folded in character and the ice dome near its center is probably less than 10,000 feet high. Where these land masses come in close contact, a high-faulted mountain forms a backbone to the whole continental mass. Between the continental glacial domes and these high mountains, natural troughs tend to channel katabatic surface winds off the Continent.

During the forthcoming IGY, glacial and seismic programs will add greatly to our knowledge concerning the thickness of the ice cap and the surface beneath. Not only will we have a more reliable concept of the Continent but it is likely that the Antarctic will never again be unpopulated even though the geopolitical rivalry for national territorial claims will no doubt continue for many years to come.

Fundamentally the purpose of this paper is to present a general impression of the continent of Antarctica and its surrounding waters. The factors of technology which have postponed exploration of Antarctica until this age will be discussed first, and then the approaches to the continent and its general physical appearances will be described.

Fear was sufficient reason alone for the early navigators to avoid the Antarctic. Their small sailing ships, caught in the grip of the southern ice, had little chance of survival. The economic drive of the fur and oil industry drew the earlier nineteenth century mariners further south into treacherous waters and still their wooden ships powered by sail were no match for the ice when it gripped them. As the nineteenth century wore on, man was growing more and more curious of what lay beyond this icy boundary and gradually mustered courage to press in as far as possible, until a number of mariners sighted land here and there.

It was Charles Wilkes, leader of the United States Exploring Expedition (1841–42), basically in quest of new knowledge, who first sighted enough of the Antarctic continent to label it as such. By the twentieth century man had reached the continent and begun to base upon it for existence the year around.

Sailing ships now had auxiliary engines which aided when wind failed, but still the earliest twentieth century ships not only risked hazards but were frequently entrapped and as late as World War I one was crushed by the ice. The crew of this ship, Shackleton's *Endurance*, made a remarkable journey across sea ice and effected self-rescue.

The tools of the early explorer on land were as primitive as the early twentieth century sailing ships. Ponies and dog teams were the only substitutes for man-hauled sledges on long journeys into the interior, limiting the distance for a day's travel to ten or 15 miles. Scarcely more than a quarter of a century ago when Admiral Byrd first went into the Antarctic to renew American exploration, his barque, the *City of New York*, had an auxiliary engine capable of producing about 200 horsepower. In a few years' time this primitive mode of transportation through the Antarctic ice pack gave way to powerful icebreakers.

The U. S. Coast Guard 'Wind Class' icebreakers were first used in the Antarctic on 'Highjump' just after World War II. These modern icebreakers with 8000 to 10,000 horsepower were able to negotiate the ice pack with little difficulty and served as an escort to a fleet of thin-skinned metal cargo ships, some of which did not get through the 700-mile pack without damage. Therefore a still larger and more powerful type of icebreaker was constructed with a wider beam to permit a path that would keep the ice away from the sides of the vessels being escorted. This was the origin of the *USS Glacier*, the latest and most powerful of the American icebreakers, if not the most powerful icebreaker in the world. Its ten diesel engines are capable of producing some 21,000 horsepower. The modern icebreaker therefore is high on the list of new tools that now permit the Antarctic continent to be unveiled.

The first successful use of aircraft did not take place until 1928 when Wilkins and Byrd brought aircraft into Antarctica as a tool of exploration. This was the beginning of the mechanical age in Antarctica, although another decade was to pass before tractors were to become highly successful as a means of surface transportation. As early as 1910 Scott introduced the first prototype of a mechanical over-snow vehicle which unfortunately was as primitive and unreliable as automobiles of that period. In 1934 Byrd introduced low ground-pressure tractors capable of competing with dog sleds for travel over well-established trails. Even as late as 1940 on the U. S. Antarctic Service Expedition dog teams were still the most reliable means to carry on extended travel into unchartered country.

In the meantime the development of aircraft technology grew rapidly, and the Byrd, Ellsworth, U. S. Antarctic Service, and Ronne expeditions showed that ski aircraft landings on the inland snow surfaces were a feasible means of working in the interior. Operation DEEPFREEZE has moved travel technology onward apace, providing new tools which include low ground-pressure tractors weighing as much as 35 tons capable of doing many times the work of a dog team. Wheeled aircraft of a multi-engine type have been successfully flown into the continent to prove that it is now possible to approach the continent virtually at any season of the year without having all activities confined to the season when the ice pack can be breached. Intrepid as the early explorers may have been it was necessary to await the development of modern technology in order to complete the mapping of the outlines of the Antarctic continent and to explore the interior.

At the beginning of the twentieth century the means of recording geographic features was still limited to hand-drawn sketches, surveying, or early photography, little advanced. Aerial-survey cameras were introduced along with aircraft, and their development has been as rapid. Navy aircraft on Operation DEEPFREEZE traveling at speeds exceeding 200 miles per hour carried fully automatic trimetragon cameras aimed forward, downward, and to each side. Supplementary data photographed included radio-altimeter and radar scans of the horizon in addition to basic flight data. The automation was so complete that the Navy dispatched pilots and technicians rather than trained geographers to explore the interior of Antarctica.

It is unnecessary to enumerate the improvements in communications from the days of Amundsen's and Scott's trips to the Pole to present day radio nets that link units of expeditions together as well as uniting them with the rest of the world. This has added succor to those who suffer the isolation of an Antarctic expedition.

Expedition men in the early part of this century still suffered from malnutrition and vitamin deficiencies. The last two decades have seen not only vast improvement in food but also in shelter, clothing, and personal comforts. The Continent is rapidly approaching the period when long-term habitation will become possible.

Without such growth in technology a description of Antarctic geography would be a sparse topic indeed. Our knowledge of Antarctic geography has been growing very rapidly, and with new scientific tools and technology much more will be learned within the next two or three years of intensive activity in Antarctica.

A review of Antarctic geography must begin with the oceans which surround the Continent in an unbroken wreath permitting currents and weather to circulate freely and uninhibited on an almost unending march about the Continent. In contrast to the division between the temperate and sub-Arctic and between the sub-Arctic and the Arctic which are largely defined by vegetation lines, the primary boundaries which delineate the corresponding regions in the south are of a different nature. The Antarctic convergence delineates the boundary between the southern sub-temperate and sub-Antarctic. Oceanographers are prone simply to designate this line as the division between the temperate and Antarctic, but as oceanographers they neglect consideration of the still greater climatic changes farther south. Although the convergence is an oceanic line it is readily detectable by human senses. There is an abrupt change in temperature by several degrees because this line is where the frigid Antarctic waters knife beneath warmer waters to the north. To the voyager on shipboard this sudden change of temperature in either direction is readily felt. Likewise, there is a change in amount of cloudiness and naturally the presence or absence of ice on each side of the line adds an awareness to the sharply contrasting convergence. The oceanographer and biologist, of course, have still greater perceptions for this change between the warm and cold waters. Plant and animal life in the ocean change abruptly as does the bird life overhead; also the mineral content of the waters varies as would be expected. The Antarctic convergence extends unbroken completely around the continent. However, its latitude varies from place to place and slightly from season to season forming a rather irregular encirclement of the Continent. The convergence lies close to the 50th parallel on the Indian and Atlantic Ocean sectors. It retreats to higher latitudes south of South America and New Zealand with a noteworthy extension northward in the proximity of longitudes 130° to 140° W. As one progresses southward toward the Continent which itself is somewhat circular, most of the visible and invisible geographic features also adhere to a concentric circum-polar shape. In the ocean depths, ridges seem to take on this same wreath-like form around the continent.

The next important line that one encounters moving southward is the ice-pack line which is considered by some to be a truer boundary between the sub-Antarctic and the Antarctic, although this definition is controversial, and some would even prefer to accept the astronomic line of the Antarctic Circle as an adequate definition of the separation of these climatic zones. The northward limit of the floating ice pack may at times coincide with the convergence but of course varies from season to season, and in the late summer may be absent all the way to the coast of the Continent itself. At the close of the winter season the frozen sea surface may extend from the Continent edge northward for hundreds of miles. Later as the summer advances the ice breaks up into smaller and smaller pieces, and the wreath of floating ice gradually moves northward wasting away as it goes. Again the northern fringe of this ice pack tends to form a sharp contrasting line at which weather changes are perceptible. The heavy seas running to the north calm down due to the weight of ice on the surface. Once again there is an abrupt change in the flora and fauna. Whales roam the edges of the pack, bird life changes abruptly and the floating ice provides refuge for seals and penguins as well as for myriads of flying birds.

An ideal ice pack such as that just described does not exist all the way around the Continent. In some favorable areas such as the Ross Sea the annual movement of the ice pack is generally predictable, and the open water back of the ice pack after it moves north has long been used to great advantage by expeditions penetrating that region of Antarctica. By contrast along other coasts, such as those of the southern-most Pacific there are to be encountered concentrations of dense packs combined with innumerable icebergs. Up to the present time modern ships found it difficult, if not impossible, to penetrate to some of the coast lines. In principle, however, for most of the Continent, a narrow to wide band of water in late summer separates the floating ice from the Continent itself.

Except for the deep penetration of the Ross and Weddell Seas and the extension of the Palmer Peninsula Antarctica would be roughly circular. However, such features do exist and the constriction created by the two great seas tends to suggest a structural division between the two major parts of the Antarctic, even though there is no reasonable remaining doubt that the two portions are actually separated by a below-sea-level channel. Because the zero and 180th meridian conveniently divide the Antarctic along an axis close to that of a line drawn between the Ross and Weddell Seas, the two portions of Antarctica were named by Nordenskjold, in 1903, East and West Antarctica.

West Antarctica lying mostly within the western hemisphere is only about half as large as East Antarctica which is generally extended beyond the limits of the eastern hemisphere to include the geographic pole and a portion of land extending up to the great Antarctic horst. East Antarctica is believed to be a massive Precambrian shield superimposed by a great dome of snow and ice rising toward the center to an excess of some 13,000 feet in elevation. By contrast West Antarctica is more folded and Andean in character. The ice dome near its center is probably well under 10,000 feet in height, although many of its mountain peaks are much higher. Where East and West Antarctica come in close contact a high faulted mountain forms a backbone to the whole continental mass. This gigantic mountain range rising to heights between two and three miles high is superimposed by flat lying Beacon sandstone which is fossiliferous and coal-bearing.

The whole of Antarctica is basically under a heavy mantle of snow and ice typical of continental glaciation. The continent is the highest of all the landmasses of the Earth and rises abruptly from the sea spilling the inland ice down through countless glaciers varying from typical classic mountain and valley glaciers to almost formless piedmont types. Some places the glaciers extend outward into shallow seas to form long tongues which may persist for many years before breaking loose. In other areas, extensive low flat-lying shelf ice extends for many square miles. The largest by far is that portion covering the southern extension of the Ross Sea which is known as the Ross Ice Shelf, about 500 miles wide east and west by 400 miles north and south. This sheet averages perhaps 600 and 1000 feet in thickness. It grows seaward at an average rate of about four feet per day and cyclically breaks back corresponding amounts once or twice a century.

Because the South Pole is near the center of the Continent and therefore latitude lines run roughly parallel to the coasts, the characteristic motif of concentric circles mentioned earlier also characterizes the isotherms of the continent and to a large extent the isobars as well. Basically the interior of the Continent is desert-like in every respect. Annual precipitation is low and, except in the vicinity of rocks where some melting occurs, it is completely denied to plant life. Thus the interior of the continent, except for bacteria and plant spores and primitive life on mountain peaks, can generally be thought of as sterile. Only a few attempts have been made to measure the thickness of the ice cap; these are still too scattered to give any positive information as to the nature of the land underlying most of the interior glacier. The traverses planned for the IGY will go far toward providing knowledge of the character of the interior. It can be expected that no features of major significance will go undetected by the end of this coming study of the Antarctic.

In this past season a considerable portion of the heretofore unknown parts of East Antarctica were seen during flights of the U. S. Navy aircraft. Beyond the high mountain fringe of Victoria Land where the mountains rise two or three miles in height the great plateau of snow and ice behind was found to rise toward the interior. The highest point reached by the planes flying above the gradual rising flattened dome of a typically conceived continental glacier was in the vicinity of latitude 80°S and longitude 50 to 60°E. The existence of some such high feature in this vicinity was predicted by *Lamb* and *Britton* [1955]. Their prediction was based upon the analysis of the behavior of meterological phenomena around the edges of the Antarctic continent. They said as follows

> "... The prevalence of certain air streams and depression movements has yielded suggestions that there may be a major divide, ice crest, or mountain range, of the order of 4000 meters (12,000 to 15,000 ft) or more in general height near the axis of East Antarctica about 80°S 80°E and running roughly parallel with the 140°E meridian ..."

Further on their prediction continued

> "... The phenomenal preponderance of southerly winds of great strength at Mawson's Terre Adelie Base, Cape Denison (67°S and 143°E) in Commonwealth Bay, is probably a topographical effect, though the topographical features which could explain it have never yet been found. This may be an example of persistence over the ice, for unknown, and perhaps great distances downstream of concentrations of the windflow in some unknown channel far in the interior ..."

It would appear basically that both of these predictions were well-founded. The highest point of the ice dome reached was close to 13,500 feet or more in approximately the position as predicted. Between this dome and the mountains of Victoria Land the cap gradually slopes down to form a broad trough-like feature running parallel to the western side of the mountains of Victoria Land which form a 'picket fence' to hold back the ice. This trough, of course, averages between one and two miles in height above sea level and has a very gradual incline from the vicinity of the geographic pole to the coast. On the mountain-walled side of the east of the 'trough' glacial outlets help to control the height of the ice and must permit an outspilling of much cold air not fully channeled in this broad trough. It is unlikely that all of the wind necessarily flows north to the Adelie Land coast. The exact shape and nature of this trough must await the detailed studies of the data collected by Operation DEEPFREEZE I and subsequent exploration. Cold katiabatic winds particularly in the fall and winter periods roll down slopes on their way to lower elevations and in such a trough could well gain momentum sufficient to account for the speeds measured by Mawson. He recorded that wind velocity at his camp for a whole year averaged 40 miles per hour as contrasted to the windiest month at Little America on the Ross Ice Shelf which averaged only 14 miles per hour. The strongest recorded wind at Cape Denison averaged 90 miles per hour for a whole day and reached a maximum speed of 200 miles per hour. At Little

America the strongest wind ever recorded in some four years of observation was only gusts up to 75 miles per hour.

To some who have flown over the interior of Antarctica the surface appears to be featureless to an absolute extreme. However, to the discerning eye the surface with its drift patterns tells a constant story of the dynamic actions of the winds of the interior. The dominating wind lines can be seen and interpreted as one might read a book. Where the lines are deeply etched and strongly in one direction one can safely predict that there have been heavy winds predominately in one direction, but where the patterns overlie one another it is obvious that one wind is not persistent or strong enough to erase the effect of other winds and therefore variability or lightness are predictable. The region close to the South Pole itself had some of the most interesting patterns that have been seen. There were several criss-crossing predominant patterns suggesting lightness of winds, but in addition there was a peculiar sastrugi pattern suggesting the form of fantail fish swimming along. There was a specific head from which three or four wavy tails extended out in a delta form. All of these snow features were lined up in one direction adding to the striking characteristic. It is believed that each of the 'tails' represented a slightly modified direction of the wind forming small drift patterns from a single obstacle of unevenness on the surface.

It is to be hoped that during the IGY concentrated efforts will be made to develop interpretation keys of the many types of sastrugi and in turn the physical characteristics and dimensions of these patterns be measured on the surface. This in turn will permit a wide scale analysis of aerial photography taken over the interior of Antarctica.

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Antarctic Photogeography

JOHN ROSCOE

Abstract—The employment of air-photo analysis as a geography research technique is termed photogeography; those skilled in this practice are called photogeographers. In Antarctica, the only continent where the existing aerial photographs contain more geographic and related information than do the maps and publications extant, aerial-photo analysis assumes an unusually significant importance. Since the first aerial photographs were made in 1901 by Scott and von Drygalski, approximately one-fourth of the Continent has been photographed, but only a small portion of the area covered has been examined by surface parties. This photography forms a permanent record of the Antarctic landscape at a given time. Since the area is one of extremely limited accessibility, a significant portion of what is to be learned about the Antarctic must come from this source.

Antarctic aerial photographs have five prospective uses, all of which will be important to IGY scientists. They are: (1) illustration, (2) map making, (3) accessibility studies, (4) detailed area studies, and (5) detailed functional studies (for example, glaciology, morphology, geology, place names, climatology, zoology, oceanography, and aurora and airglow). The status, value, and prospects of Antarctic photogeography are discussed.

Photogeography is the analysis and interpretation of airphoto images as a geographic research technique.

During the last century, botanists, zoologists, geologists, and other scientists have published several thousand papers based on detailed laboratory studies of field samples brought back from Antarctica. Excellent data have been developed from these samples by scientists who never left their home towns. Meanwhile, scientists from disciplines like geomorphology, which do not readily lend themselves to sample collecting, have had to return with only the observations they could record and their memories. Furthermore, these data were not suitable for independent study by colleagues who did not accompany the expedition. For many of these scientists, aerial photography has become a worthy equivalent to the collection of field specimens. Previously unknown iceforms have been found, buried coastlines located, maps redrawn, rates of glacial flow determined and many geographic discoveries have been made through the analysis of Antarctic airphotos by scientists, who though competent in their disciplines, have never been in the specific area concerned.

Airphotos as permanent records—Each airphoto, properly titled and indexed, will stand as a permanent record of a portion of the Earth's surface at the time the film was exposed. Time may adversely affect the memory of the explorer, but the airphoto does not suffer from the effects of time, provided the film is properly preserved. At any time in the future, scientists with increased technological means will be able to use these same data (airphotos) to check our analyses and perhaps to derive considerably more information.

Comparative analyses of Antarctic airphotos taken from one to ten years apart have already revealed much information about the rate and nature of ice movements as well as the ephemeral character of some of the ice forms. For example, comparative analysis has revealed that the Publication Glaciers and Ice Tongues at the junction of the Lars and Ingrid Christensen Coasts have advanced an average considerably in excess of 30 feet per day during the ten years between 1936 and 1946 [*Roscoe*, 1952].

Airphoto reconnaissance in Antarctica—The first few airphotos of Antarctica were made from captive balloons by Scott and von Drygolski during their expeditions of 1901. At the time they were made, these large-scale airphotos revealed hitherto unknown information about the character of sastrugi and other ice forms. Today, the value of these airphotos is of a different character. They are the only reliable record of certain coastal areas which have since changed radically in configuration.

The first airplane flights and airplane photographs made in Antarctica were made in the summer of 1928–29 by Wilkins and Byrd on separate expeditions. During 1929–30, one year after the introduction of airphoto reconnaissance, four major expeditions, those of Byrd, Wilkins, Mawson, and Christensen, all were engaged in taking aerial photography of the Antarctic.

Byrd continued the aerial survey of Marie Byrd Land and the Ross Shelf Ice in 1933–1935. John Rymill, leader of the British Grahamland

Expedition, 1934–1937, continued the airphoto survey of the Palmer Peninsula, concentrating on the central section of its west coast. Lincoln Ellsworth, on his historic flight across Antarctica from the Weddell to the Ross Seas in the summer of 1935–1936, took 66 airphotos of landmarks in this previously unexplored area with a 35-mm camera.

In the following summer, Consul Lars Christensen's sixth expedition made oblique aerial reconnaissance photography for much of the coast of Queen Maud Land. Maps have been made from this photography.

The Deutsche Antarktische Expedition, 1938–1939, under Alfred Ritscher, began the first large scale aerial photographic attack on a portion of the Antarctic interior, which resulted in three published maps of some 350,000 sq km of previously unexplored land. Again photosurvey and photogrammetric instruments were used in exposing the photography and in preparing the maps, but the maps still could not be said to be precise because of a lack of ground control points.

The U. S. Antarctic Service Expedition, 1939–1941, considerably expanded the photo coverage of Marie Byrd Land and the Ross Shelf Ice as well as making an airphoto survey of Charcot and Alexander I Islands and of the southwest and southeast coasts of the Palmer Peninsula. Aerial color photography was used experimentally for the first time in the Antarctic. The technique of flying photo circles was practiced, giving effective panoramic views from air stations located over geographic positions which contained some elements of ground control.

From 1941 through 1946, the countries of the Northern Hemisphere were too busily engaged in World War II to consider Antarctic exploration. An Argentine expedition in 1943 took oblique airphotos in the vicinity of Port Lockroy, however.

In the 1946–1947 season, the U. S. Naval Task Force 68, planned and executed an intensive photo reconnaissance survey of the coasts of Antarctica. Previously, only oblique photography had been used, but the aircraft of Task Force 68 were provided with trimetrogon installations which permitted horizon-to-horizon cover and vertical photography of the path of flight. 'Gremlin' cameras were installed to provide additional data for mapping controls. Sixty-five thousand aerial negatives were exposed by the expedition's 12 long-range aircraft, operating from two Task Groups based on seaplane tenders at sea and a third Task Group based on the shelf ice at Little America. Most of the coast between 15° E and 170° E, and between 95° W, and 130°W, was photographed by single, double, or even triple trimetrogon flights parallel to the general shoreline, with occasional sorties into the interior averaging 200 miles in depth. Photo reconnaissance was also carried out over parts of the polar plateau, including the South Pole and the plateau areas east, west and south of the Ross Shelf Ice.

In 1947 and 1948, the Royal Australian Air Force photographed Macquarie and Heard Islands.

In 1947–1948 the U. S. Naval Task Force 39 sent surveyors ashore at selected points to obtain the ground control necessary for the utilization of the previous season's aerial photography for mapping purposes. In addition, vertical airphotos were taken of the Davis Sea coastline, Bunger's Hills, and the junction of the Knox and Budd Coasts. Low altitude obliques were made of these areas, as well as McMurdo Sound, Little America, Peter I Island, and Neny Fjord from helicopters. Altogether 10,000 additional airphotos were made.

Meanwhile, the Ronne Antarctic Research Expedition was busily engaged in a trimetrogon survey of Alexander I Island and both coasts of the Palmer Peninsula to their southernmost limits. Ronne's principal accomplishment was the discovery of the Weddell Sea Shelf Ice and Edith Ronne Land to its south. He returned with 14,000 trimetrogon prints of these areas and a measure of ground control.

The combined British-Norwegian-Swedish Expedition, 1950–1952, produced extensive airphotos of the expedition area in Queen Maud Land. Some of these were over areas photographed by the Germans, and provided valuable comparative photography.

After World War II, the Argentine and Chilean governments established a dozen military bases in the Palmer Peninsula area. Airphoto reconnaissance activities have become standard operating procedure on the annual resupply expeditions to these bases.

The Soviet Union Expedition at Mirny is equipped with several photo reconnaissance aircraft and a corps of photo interpreters. The reports radioed from the main Antarctic base indicate that the Russians flew over 15,000 sq km of territory and made preliminary photo interpretation within the first few weeks of their occupancy. Already maps have been published.

The British Falkland Island Dependencies Survey also has eight occupied bases in the Palmer Peninsula region around which airphoto coverage has been made. In 1955, the British let the first commercial contract for airphoto mapping of the Antarctic. The Hunting Aerosurveys Expedition, including one ship, two flying boats, two helicopters, and ground control point survey teams has successfully completed its first summer's work in the northern Palmer Peninsula area.

Photogrammetrically speaking, Antarctica has finally reached the status of the other continents, having completed the aerial reconnaissance cycle from early captive balloon photography to standard commercial aerial surveys.

Status of Antarctic airphoto coverage—Except for major parts of the Caird, Luitpold, and Eights coasts, the entire perimeter of Antarctica is now essentially covered by aerial photography of one variety or another. This coastal coverage is thin in some areas, but in most regions it extends inland from one hundred to three hundred miles. Marie Byrd Land, the South Polar Plateau, the lands surrounding the Ross Ice Shelf, and Palmer Peninsula are particularly well covered.

Aircraft have now flown over about half of the huge polar ice cap covering the continent. In general, these aircraft have photographed the interior areas seen which differed morphologically from the high, relatively featureless ice plateau.

Perhaps a third of the continent still remains to be seen or photographed for the first time. We will not know the exact area until after the flight tracks and airphoto indices are worked out for the 1955–1956 season.

While complete airphoto coverage of mapping quality is a goal yet to be met, an appreciable portion of Antarctica is covered by reconnaissance aerial photography. More information, more reliable information and more detailed information about Antarctica is available from today's airphotos than from existing maps. A program is needed to reduce this information to large-scale map and text forms.

Limitations to airphoto reconnaissance in Antarctica—There are no significant differences in the photo reconnaissance and interpretation methods used in Antarctica and those used for more temperate regions. There are, however, important limitations imposed by the local environment which cause both qualitative and quantitative losses in the airphotos available for interpretation. The factors which impose the most severe limitations are the difficulties involved in flying. These are:

(1) *Bases.* There is a large area centered about the South Pole in which there are no air bases suitable for exploring aircraft. Landing of ski or wheel equipped aircraft is possible in certain regions but the base equipment required is lacking.

(2) *Logistic support.* Everything used by the flying explorer, including all spares and repair equipment for his aircraft must be carried to the base.

(3) *Navigation.* Loran, shoran, and radio range systems are not available. The Sun is not visible in the long winter night and the stars are unavailable for celestial navigation during the summer day. Magnetic compasses are frequently useless. Adequate maps are not available. Known landmarks are not often charted correctly.

(4) *Weather and climate.* Even during the optimum flying season between September and February, suitable weather is limited to a few hours or days at a time. Frozen spray at take off limits seaplanes and flying boats. Frequently, surface winds in the area being photographed blow the loose firn along the ice cap surface, effectively blurring the terrain from observation.

(5) *Light conditions.* First, the long winter night prohibits practical airphoto reconnaissance for a sizable portion of the year. Secondly, high overcast causes the Antarctic phenomenon known as 'white day,' during which the intense diffusion of light eliminates the horizon and all shadows, everything appears the same misty degree of white, nothing may be photographed or seen, and the pilot is fortunate not to crash into high flat terrain. Finally, during large portions of the year, the Sun is either at or near the horizon during which time oblique airphotos on the sunward side of the aircraft may have to be taken directly into the Sun.

(6) *Topography.* The Antarctic ice cap rises to heights in excess of 13,500 feet. Relatively few aircraft with sufficient range and of the type which can be based in Antarctica can fly sufficiently high above the icecap to permit effective airphoto coverage at reconnaissance scales. Uncharted, snowcovered mountains, penetrating this icecap, cause further problems. Oxygen supply is another difficulty.

(7) *Photo processing.* If a complete field laboratory is not available, camera failures and substandard coverage will not be recognized until the return of the expedition. If a laboratory is available, its supply forms a logistics problem. Even the fuel and water necessary impose significant difficulties. Moreover, the lab technician must be specially trained in the development and printing of photography of ice terrain, which consists only of delicate shades of very light gray. (Snow, firn, and glacial ice differ only slightly in photographic appearance.)

(8) *Required supplementary data.* If the photography is to be used for mapping in the unexplored

Antarctic, ground control parties must occupy many surface stations along the line of flight. A 'gremlin' camera set to photograph such instruments as chronometers, thermometers, inclinometers, radio altimeters, pressure altimeters, etc., and data cards will, when combined with pilot's log and navigator's tack chart, permit the airphoto analyst to compute such factors as scale, general location and orientation of the airphotos.

While all these factors tend to limit aerial reconnaissance, it is still, by far, the most profitable method of obtaining data relative to the Antarctic terrain.

Status of Antarctic air photogeography—Aside from providing the topographical and glaciological detail for maps of the Antarctic, airphoto analysis has performed numerous other services. Many ice forms previously known or described have been isolated and defined. Examples of these include floating fissures, reentrant rifts, right angle drifts, channel glaciers, and ice morass. In addition, much information relative to the structural forms and the depositional and erosional processes affecting many continental ice forms has been confirmed, denied or modified. Analysis of comparative photography has provided us with information relative to ice movement.

Photogeography has also been used to select major base sites and to plan accordingly prior to expedition departure. The interpretation of airphotos of 1:20,000 scale can reveal such detailed information as the presence of certain types of bacteria on the surface to a scientist who is familiar with Antarctic ecology.

One recent test of photogeography in the Antarctic was a geographical, glaciological, and geomorphic analysis of a 400 mile extent of coastline largely unexplored by surface parties. The analysis of the area, which also discovered 100 miles of previously unknown coastline buried beneath the ice, has since been confirmed as accurate by the first scientific party to visit the region.

Because the Antarctic is an area of extremely limited accessibility, we must face the fact that a truly significant portion of what we are to learn about the area and its phenomena must come from the analysis of aerial photographs by qualified scientists.

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The Weddell Sea Area

FINN RONNE

Abstract—The Weddell Sea area is considered here as one possessing high strategic importance for exploration and study in connection with the IGY program. Tentative plans are presented for United States ships to penetrate severe pack-ice conditions and establish a base, giving full consideration to current Weddell Sea activities by Argentine and British parties. The historical background is considered and the potential scientific and geographical gains are weighed.

Two huge bodies of water pierce the otherwise roughly circular coastline of the Antarctic continent. One is the great Ross Sea, south of New Zealand and the other is the even larger Weddell Sea (Fig. 1), southeast of the southern tip of South America. Both are major geographical features within the Antarctic Circle and both bear names of their respective discoverers. The Weddell Sea, bounded on the west by the Palmer Peninsula and to the east by Queen Maud Land, is the subject of this paper.

Since it was first identified as a sea, allegedly by James Weddell in 1823, the Weddell Sea has been a fearful obstacle to penetrate. A history of frustrated efforts has caused it to be referred to as the 'hellhole' of the Antarctic. This descriptive phrase results from a devastating combination of strong winds and powerful ocean-currents which produce a concentration of forces and ice-pressures of tremendous magnitude. Depending upon these conditions at a given time, the central area of the Weddell Sea is bordered on the east, west, and north by loose to close pack-ice. The ice circles so that it generally jams against the east coast of Palmer Peninsula, forming heavier pressure than is found in other parts of the Antarctic Ocean. With the possible exception of the land-encircled Arctic Ocean, no other area of pack ice on the surface of the Earth can compare with the impassability of the central and western portions of the Weddell Sea. Even powerful whaling-ships have failed to force the heavy pack ice here. Open water leads do occasionally form in the western portion of the Sea, near the shores of Palmer Peninsula; but only after katabatic winds have rushed down from the Continent's interior to push the ice off the coast. Such a wind from the southwest must have caused leads to form along the eastern coast of Palmer Peninsula when C. A. Larsen sailed the *Jason* in 1893 in ice-free waters to beyond the 68th parallel at the 60th west meridian before being stopped by heavy ice. However, this seems to have been a unique feat, as the voyage has been attempted since but remains unduplicated.

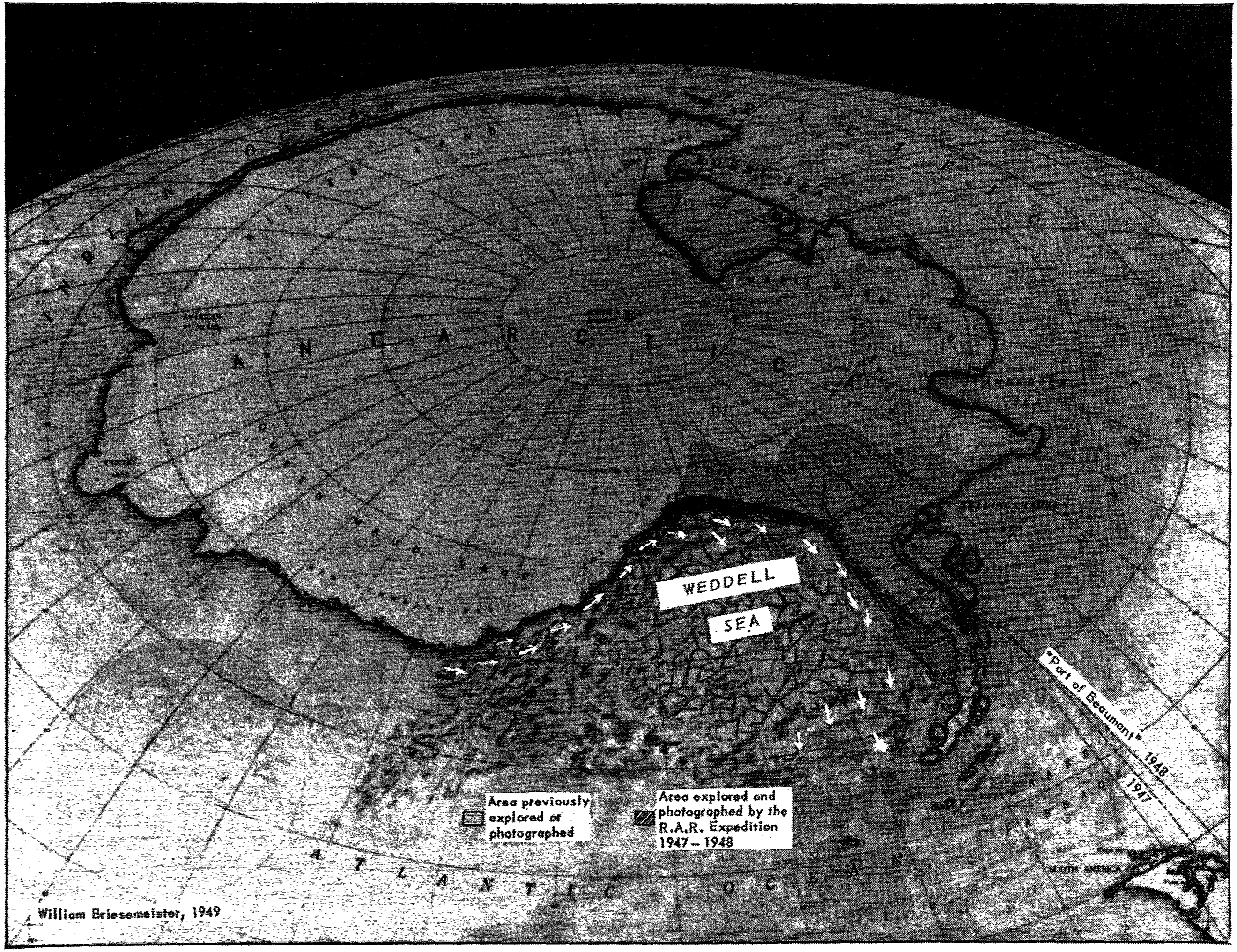
In 1913, Filchner's ship, the *Deutschland*, was the first to reach the head of the Weddell Sea by an approach from its eastern side. The expedition was erecting its base huts when the ice shelf suddenly broke loose and drifted northward. The men were rescued but the ship, beset, encountered the full fury of the ice-pressures in the central portion of the Sea. It was 10½ months later, after drifting about 1100 miles, before open waters were reached.

In 1915, Shackleton in the *Endurance* reached within a few miles of his destination, Vahsel Bay, when the ship was beset and began her drift northward, also in the central portion of the Weddell Sea. The ship was subjected to such intense pressure that her sides were crushed and she eventually sank near 69° S, 52° W. This expedition's precarious months of existence while drifting northward on the ice-floes is one of the most dramatic stories of a hair-breadth escape. Upon reaching open water, their whale-boats were launched to obtain outside aid, and not a man was lost.

That not even a modern ship can force the ice pack in the central part of the Weddell Sea was shown as recently as this past January, when the *Theron*, transporting a British trans-antarctic expedition, became hopelessly trapped for 25 days. When finally released, the ship was at a point north of her entry. The next attempt was made further to the east where she successfully reached her destination.

Much of the information available on the ice conditions in the Weddell Sea is the result of bitter experience by the early explorers in this area. Not specifically built for forcing the ice, their ships were small and under-powered. The *Deutschland*, for example, had a 300 horsepower steam-engine, while our latest icebreaker has 21,000 horsepower diesel-electric drive and is equipped in every way to do the job.

Ocean currents close to the Antarctic Conti-



William Briesemeister, 1949

FIG. 1 – Overall map of the Antarctic Continent showing the ice concentrations and movements in the Weddell Sea

nent's shores flow in a westerly direction. With a speed of less than one knot, the current is setting towards the southwest at the eastern entrance of the Weddell Sea and flows approximately parallel to the main direction of the Queen Maud Land coastline. The current sweeps into the southern boundary of the Sea at 77° S before turning northward, carrying the ice floes with it. A ship aided by this current could reach the open water fronting the Filchner Ice Shelf without difficulty. This current, therefore, generally keeps the waters ice free in this latitude from Lassiter Coast on Palmer Peninsula to Luitpold Coast. On our 1947 flight, leads extending for some ten miles off shore were sighted northward, all along the eastern coast of Palmer Peninsula. Ships successful in navigating the Weddell Sea generally found open water or loose pack ice in the eastern area by following a course close to the Greenwich meridian and ten degrees west longitude. Ross in 1842, Bruce in 1903, and Riiser-Larsen in 1930 all followed this course as did the *Norsel* during the 1950–51 and 1952 seasons. The most recent ships to penetrate here were an *Argentine* ice-breaker and the *Tottan* of the British IGY party which set up a base to the north of Vahsel Bay last January.

Timing of ship penetration is important. In 1951, the *Norsel* reached the continental shores on December 23, and found easy sailing. At the turning point of our flight in early December 1947 to the southeastern corner of the Weddell Sea, we observed open water to the horizon in northeasterly direction toward Queen Maud Land.

The configuration of the land and topography is at great variance in this sector. The 6000 ft elevated Palmer Peninsula plateau forms the western boundary of the Weddell Sea to about 76° S. The plateau continues southward into the unknown

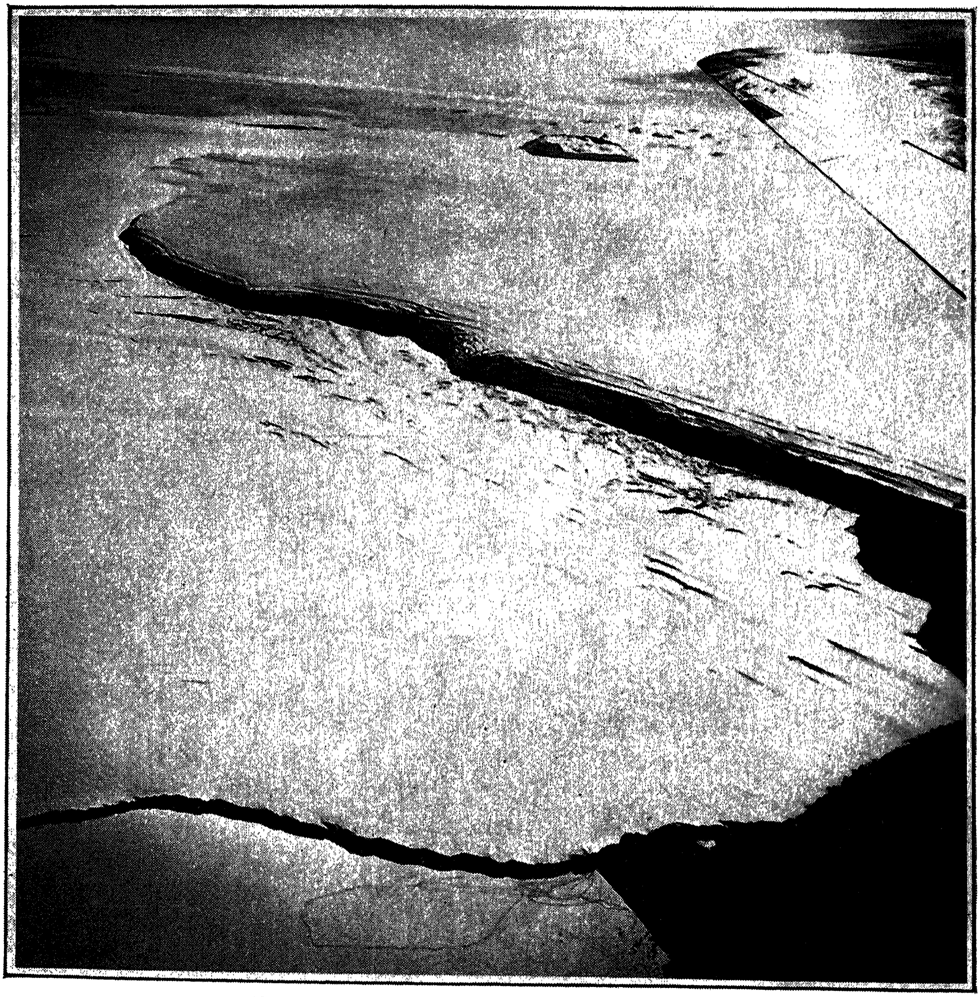


Fig. 2 – Bowman Peninsula and Austin Mountain

where it presumably blends into the 10,000 ft south-polar plateau. For its entire length, the peninsula itself is rugged with massive mountain chains up to 12,000-ft elevations. Popular belief holds that in geologic history there was a connection between Palmer Peninsula and Patagonia. Some observers note similarities in the eruptive rocks and geological formations in both areas. Although the United States Antarctic Service expedition in 1940 made valuable geological contributions, the structural connection of the Palmer Peninsula mountains to the South American Andes as well as to the mountains in the Ross Sea area has not been affirmed or denied beyond reasonable doubt.

The south central portion of the Peninsula is smooth, broken only by scattered peaks protruding through the ice sheet. The mountain-dominated stretch of coast is broken by capes and inlets with glaciers flowing seaward from the higher inland elevations. Glacial and tabular icebergs are frozen into the coastal ice which is broken by a few open water leads. A sledge party can use this coastal ice with safety and obtain seals for feeding their dogs, as animal life was observed when flying over it. On the sea ice in front of Bowman Peninsula (Fig. 2) in the southwestern corner of the same situation, tracks of seals and penguins were seen. Since the pack ice leads are wide and plentiful during the Antarctic summer, whales can inhabit these remote waters and withdraw northward before the freeze-in. Our flights were always at an elevation of 10,000 feet or more, too high to spot whales.

Two of our flights followed the edge of the shelf ice (Fig. 3) at the head of the Weddell Sea. Celestial observations proved the ice front to be about 70 miles farther south than reported by Filchner 34 years earlier. One of two things could have hap-

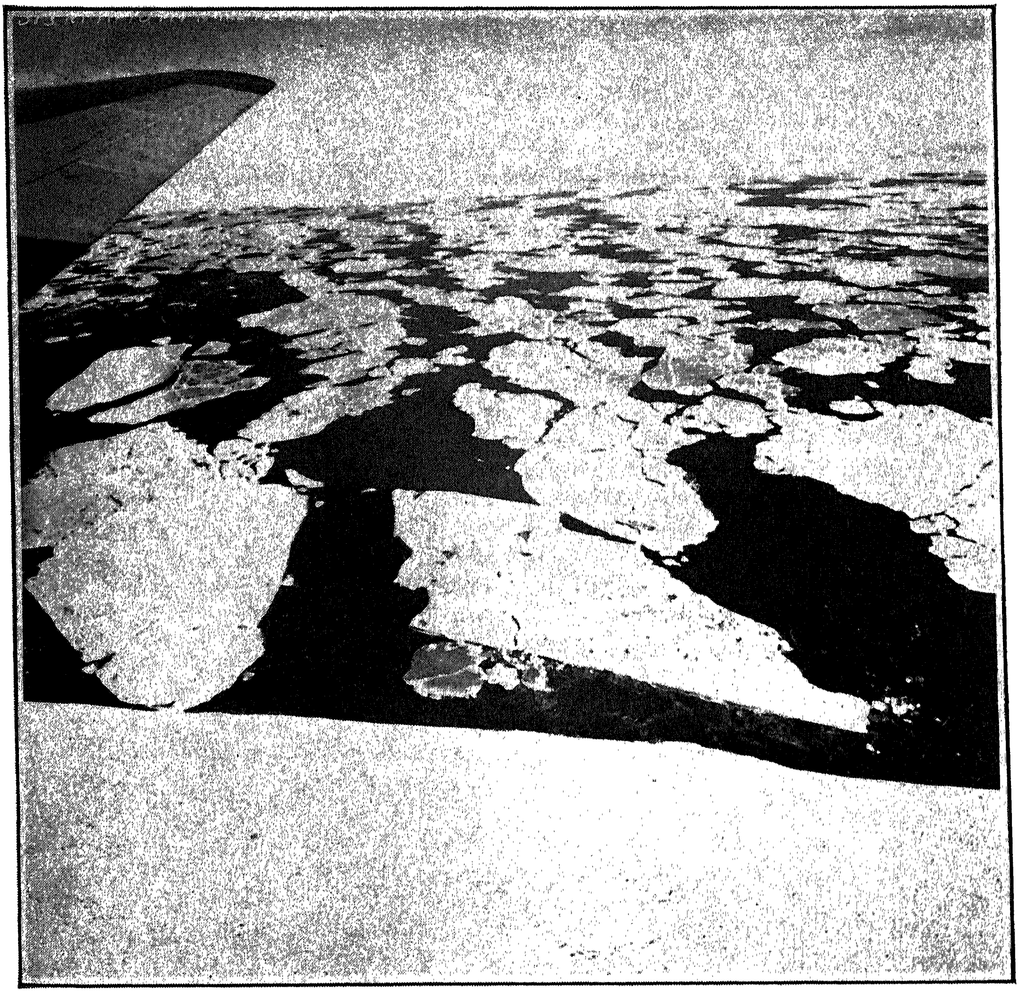


FIG. 3 – Open pack ice in the Weddell Sea

pened: (a) the floating shelf ice might have broken off gradually for the distance of 70 miles, since it is afloat and subject to pressures originating at the higher inland elevations, similar in structure to the Ross Shelf Ice; or (b) Filchner may have assumed he was sailing along the ice front when he actually may have been skirting a huge tabular iceberg which had broken off and was drifting northward.

Filchner Shelf Ice from the air appears smooth, except for a crevassed area about 30 miles long, parallel to and about three miles from the edge. Smaller disturbances sighted further inland and higher elevation toward the southern horizon indicate that only the sea-ward part of the shelf-ice was afloat. The deeply indented Gould Bay at 44° W longitude was a definite break in the otherwise smooth, straight-running ice edge. The bay, filled with sea ice and a few glacial icebergs, measured about 20 miles across. The land south of the bay was crevassed, and rising in elevation as indicated by our radio-altimeter readings. At a point 70 miles from the edge, the surface was 700 feet above sea level. This coupled with earlier observations in this key area led me to assert that the Antarctic Continent is a single unit, not divided by a frozen body of water between the Ross and Weddell Seas as some geographers had conjectured. Preliminary reports of Operation DEEPFREEZE seem to substantiate my 1947 observations. Their observers report seeing mountain ranges in about 85°, to the south of our 1947 flight-track. Although on such a long flight it would be next to impossible to plot a flight-track precisely, the Navy fliers estimated that their turning point was about 100 miles short of the Weddell Sea, where their radio-altimeter indicated a surface elevation of 700 feet. Open water or pack ice had not been seen on that flight.

Bordering the Weddell Sea to the east, the coast is one long line of barrier-cliffs showing no evidence of being aground, except at 76° S where the tide marks were seen on the ice cliffs. Beyond the coast are gentle slopes and glacier-covered mountains, rising to 3000 feet not far inland. A few snow-free mountains protrude through the ice sheet from Cape Norvegia southward, terminating at about 74° S, 20° W. Filchner sighted nunataks of bare rocks; but he was unable to reach any of them to report on their geological character. Knowledge of this area's geology, therefore, is still unknown with the exception of some deep-sea soundings and dredgings which suggested the structure resembles Victoria Land rather than Palmer Peninsula. Moltke Nunataks are the most southerly mountains seen in the southern portion of Luitpold Coast, for beyond lies the unknown.

Except for Admiral Byrd's exploration flights south and eastward from Little America and Ellesworth's aerial projectory from Palmer Peninsula to the Ross Sea, almost nothing is known of the interior land-mass of the continent. Because of its proximity to the still unknown interior, the Weddell Sea area offers a major challenge in Antarctic science, which will be the subject of intensive investigation during the International Geophysical Year.

A possible location for a Weddell Sea base is in Gould Bay, about 40 miles west of the Argentine base. By the end of December, the southerly winds which prevail here will have swept the sea ice out. On the other hand, Bowman Peninsula or close-by Gardner Inlet offer a more advantageous location. This would place the base about 380 miles northwest of Gould Bay. A landing is possible on the slopes of Bowman Peninsula where the land rises gradually to 1500 feet above sea level. Gardner Inlet, where the surface elevation is about 300 feet, provides a smooth surface for air-operations and easy access to the interior and other IGY stations. A Gardner Inlet base would space the IGY stations more evenly. The Argentine base would be about 450 miles to the east; and Byrd Base about 700 miles to the west. The nearest IGY station northward would be Stonington Island in Marguerite Bay, about 540 miles distant.

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Objectives of Antarctic Glaciological Research

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Abstract—Antarctic glaciological studies should focus principally upon features unique to the region and upon basic relations of world-wide significance. Antarctic ice is the greatest mass of land-locked water substance on Earth, and determination of its volume by geophysical means is needed with respect to a complete world water inventory, to a determination of Pleistocene eustatic shifts of sea level, and to estimates of possible future shifts of sea level. A prediction is made that ice in East Antarctica may prove to be as much as 3500 to 4000 meters thick and that the average thickness of Antarctic inland ice exceeds 1600 meters. Return of even a part of this water to the oceans has far-reaching geological and economic significance, but changes in Antarctic ice wastage will probably be slow enough and small enough so that the sea level shifts will not be catastrophic. Data on the past, present, and future behavior of this ice will be sought through studies of accumulation and wastage, of firn stratigraphy, of geological evidence for ancient fluctuations, and of pertinent glaciometeorological factors. Identification of annual accumulation layers is essential, and oxygen-isotope ratios (O^{18}/O^{16}) promise to be useful for this and for identifying and indicating the nature and magnitude of earlier secular climatic variations.

Deep drill holes in the Ross Ice Shelf and the inland ice will give valuable data on thermal regime and on the diagenetic changes converting snow to glacier ice in this cold environment. Crystal fabrics determined in cores from these holes should bear significantly upon the basic problem of glacier flow. The vertical profile of flow velocity will be determined by inclinometer surveys in the holes.

Study of the constitution, structure, and genesis of the Ross Ice Shelf will advance the understanding of ice shelves elsewhere. Finally, every effort will be made to recognize and date, by tritium, radiocarbon, or other means, prominent events in the history of Antarctic ice so that synchronous or non-synchronous behavior with respect to ice masses in the rest of the world can be established.

Introduction—The principal accessible elements in Antarctica are air, water, and ice. It is fitting that a major effort should be made during the International Geophysical Year to learn more about each, and particular attention should be directed to ice since more than 85 pct by area and 90 pct by volume of the Earth's land-borne ice lie in Antarctica. Unfortunately, concepts of the nature and behavior of this ice mantle are drawn largely from studies of glaciers in more temperate environments, and this is probably one reason why a difference of opinion exists [*Flint*, 1947, p. 52; *Ahlmann*, 1949a, p. 324] as to the degree of similarity between Antarctic inland ice and the Pleistocene continental ice sheets. Comparatively little is known about the constitution, environment, and behavior of the great bulk of Antarctic ice, and ven the more thoroughly investigated Greenland e sheet is not wholly analogous.

The International Geophysical Year (IGY) provides the finest opportunity in history for attacking this problem on a broad basis, but the program must be carefully focused, and the following principles are suggested as a guide in orienting the glaciological research. First, investigations should concentrate particularly upon items which are unique to the Antarctic and which cannot be more efficiently and effectively studied in more accessible areas. Second, attention should be given, insofar as possible, to basic principles and to matters of world-wide significance. Third, efforts should be made to learn as much as possible about the physical state, environment, and behavior of Antarctic ice bodies. Since more than 99 pct of Antarctica is covered by ice, the glaciologist will not lack subjects for investigation.

Consideration is given in the following pages to some lines of investigation that seem to satisfy the above principles. This discussion pertains only to research proposed by glaciologists of the United States. The comments offered represent the indoor musings of one who has never been to the Antarctic and who is deeply indebted to the writings of those that have.

Volume of Antarctic ice—For more than a century attempts have been made to calculate the rise of sea level to be expected from melting of all glaciers [*Maclaren*, 1842, p. 365]. The wide range of results, from 23 to 120 meters, before isostatic adjustment [*Daly*, 1934, p. 11; *Ahlmann*, 1953, p. 3], can be attributed to the fact that the thickness of Antarctic ice is unknown. Reasonably accurate determination of Antarctic ice volume is necessary for a total water inventory of the globe, for determining the magnitude of Pleistocene eustatic shifts of sea level, and for estimating possible sea level changes of the future. Determination of ice thickness at as many significant spots as possible should be a major objective of the IGY, and, fortunately, a number of countries intend to undertake such investigations.

Thickness measurements will be made primarily by the seismic-reflection procedure. The biggest problem will be the logistics of getting crews and equipment into the critical areas. Data are most needed for the inland ice, and United States plans call for seismic work in the vicinity of the Byrd Station in Marie Byrd Land, hopefully between there and the pole, and possibly beyond the pole in whatever direction the logistics permit. If feasible, a traverse should be extended toward the center of the great East Antarctic ice sheet, as this may be the most significant area of all. An airborne crew should have opportunity to make individual measurements at particularly significant spots. Considerable seismic work is also planned for the Ross Ice Shelf.

The need for good determinations of thickness on the inland ice is demonstrated by the fact that a figure commonly cited is 600 meters [*Debenham*, 1929, p. 19; *Flint*, 1947, p. 49], although calculations of volume assume average thicknesses ranging from 600 to 1600 meters [*Daly*, 1934, p. 7; *Flint*, 1947, pp. 429–431]. Estimates of maximum thickness exceed 2400 meters [*David*, 1914, p. 612; *Gould*, 1940a, p. 840], and *Robin*'s [1953, p. 208] recent measurement of 2400 meters of ice in Queen Maud Land has stimulated speculation that the Antarctic inland ice is thicker than formerly thought [*Odell*, 1952, pp. 29–31; *Ahlmann*, 1953, pp. 2–3].

The impression of thinness has been derived largely from West Antarctica where a mountainous terrain is not completely submerged by ice. The ice mass of East Antarctica is larger and seemingly has more the character of a true continental sheet [*Gould*, 1940a, p. 840]. Recent inferences [*Lamb*, 1948, p. 59; *Lamb* and *Britton*, 1955, p. 348] and reports [*Siple*, 1956] of elevations exceeding 4000 meters on the ice mass of East Antarctica suggest an ice mantle of considerable thickness. The prediction is ventured that between 3500 and 4000 meters of ice will be found in this area and that work during IGY will establish an average thickness for Antarctic inland ice in excess of 1600 meters.

Gravimetric surveys will also be carried on by the seismic crews and should help define minor configurations on the subglacial floor. Limited extrapolations as to ice thickness in areas lacking seismic data will be possible from the gravity work. Gravity data may also prove useful in evaluating the degree of isostatic adjustment attained in various parts of Antarctica if sufficient tie-ins with adjusted areas are possible. This procedure might possibly provide a means of estimating recent major fluctuations in ice thickness.

Plans call for the establishment of fixed seismological stations for earthquake recording at a number of Antarctic posts. Dispersion of Rayleigh waves recorded at these stations will give a measure of average thickness for the inland ice, if earthquakes occur in locations such that these waves have to traverse the Antarctic ice sheet before reaching the stations. This may prove to be a valuable method for determining the average thickness of ice in inaccessible parts of East Antarctica.

The glaciological-geophyiscal program of IGY will have been worthwhile if it provides nothing more than good figures on ice thickness leading to a reliable calculation of the volume of Antarctic ice.

Variations in volume of Antarctic ice—Ample evidence indicates large changes in volume of Antarctic glaciers in the past, so the situation is historically dynamic. Changes in ice volume, past and future, have great geological, cultural, and economic significance through their effect on shifts of sea level. At least 90 pct by volume of the Earth's land ice is in Antarctica, and these glaciers are something of a Sword of Damocles hanging over the heads of all peoples living close to the sea. An evaluation of the strength of the hair suspending this sword is in order. Consideration will be given mainly to the possibility of glacier shrinkage, as that seems to be the direction of the present change.

It has been stated that the melting of eight to 11 meters of ice over the entire Antarctic sheet would produce a world-wide sea level rise of one-third meter [*Croll*, 1875, p. 388; *Odell*, 1952, p. 53]. A rise of this magnitude in a decade would be a considerable inconvenience to the world, and melting of eight to 11 meters of ice in ten years seems not impossible. However, such a sea-level rise through wastage of Antarctic ice is highly unlikely for the following reasons.

The substance at and for several meters beneath the surface in Antarctica is not glacier ice of density 0.9 as assumed in the earlier calculations but is firn of density 0.4 to 0.5 at the most. Melting of close to 15 to 21 meters of this material would be required to produce a one-third meter sea level rise. Melting is not now a major mechanism of wastage in the Antarctic, and the climatic change required to make it important would be large. In fact, one popular hypothesis postulates that warming of the climate would produce an expansion rather than a shrinkage of the Antarctic ice sheet.

Deflation and calving are the other processes of wastage worthy of consideration. With respect to wastage from the continent, deflation is effective only where the wind blows snow into the ocean. Along the Terre Adelie coast, probably the windiest of all Antarctica, an average of 17 × 10^9 kilograms of snow is said to be blown to the ocean annually for each kilometer of coast line [*Loewe*, 1956, p. 664]. If the winds in all Antarctica should increase to be equal to those of Terre Adelie, the total rise of sea level produced by snow blown from the continent into the ocean would be only 0.3 mm per decade.

Calving is almost certainly the most important mechanism of wastage in the Antarctic, but even a sudden change in calving rate is not likely to produce a significant rise in sea level, for calving occurs primarily from the ice shelves which are in large part afloat and already displacing equivalent volumes of water. Quantitative data on calving are not available, but a sudden increase in calving from Antarctic land ice would probably produce a sea level rise not exceeding one or two millimeters in a decade.

Thus, it seems that the world population can probably relax with respect to sudden short-time rises of sea level through wastage of Antarctic ice; however the long-term picture is something else. Wastage of all Antarctic ice would cause a rise of sea level here estimated at close to 60 meters, and conceivably this might happen in 10,000 to 20,000 years.

Deep core drilling—Current plans call for the drilling and coring of two 300-meter holes, one on the inland ice at the Byrd Station and one near Little America V on the Ross Ice Shelf. From these holes and their cores valuable data should be obtained upon the following items: (1) thermal regimen of these ice bodies, (2) nature, mechanism, and depth of the transformation of snow to firn to glacier ice, (3) changes in crystallographic orientation with depth and degree of deformation, (4) former secular variations in the temperature of the environment as indicated by oxygen isotope analyses, (5) possible major climatic variations as expressed by the physical nature of the firn and ice or by structures therein, (6) vertical flow-velocity profile by measurement of subsequent deformation of the holes, and (7) the role of bottom melting or bottom accretion in the evolution of the Ross Ice Shelf. Further discussion of these items is given in following parts of this paper.

Although most core studies are best made immediately in the field, consideration will be given to the possibility of returning some selected core materials, in unaltered form, to laboratories in the United States for further analyses.

Firn stratigraphy—A primary objective of stratigraphic studies in Antarctic firn, a sedimentary accumulation in large part deposited by wind, will be the identification of annual firn layers. This identification must be placed on a firm basis in order to determine variations in annual accumulation, both regional and secular, and to relate them to physical and meteorological aspects of the environment. Identification of the annual layers is necessary for assessment of the basal metabolism of Antarctic ice bodies and is a key to their immediate past history.

The recognition of annual layering in Antarctic firn has proved difficult [*Wade*, 1945, p. 167; *Loewe*, 1956, p. 662]. By painstaking and detailed studies of density, grain size, texture, penetrability, melt features, and related phenomena, Benson (personal communication) has been able to define annual layers in the firn of central Greenland. Using some of the same techniques but relying largely on grain size, coherence, and to some degree density, *Schytt* [1956, pp. 238–241] has been the first to identify successfully and consistently annual layers in Antarctic firn.

Identification of the annual layers from properties determined in the field is most desirable, but if this proves impossible, laboratory analyses can do the job. Recent work shows that variations in oxygen-isotope ratios (O^{18}/O^{16}) can be used to identify annual firn layers (Epstein, personal communication) because these ratios reflect the differences in temperature at which precipitation occurred. An extensive sampling program is planned for oxygen-isotope analyses with the objective of checking and confirming field identifications of annual layers and of recording secular temperature variations as reflected in samples from the deep bore holes. A 300-meter hole should penetrate deposits representing a time interval of 500 to 1000 years, and the oxygen-isotope analyses will indicate the magnitude of the secular temperature variations as well as their approximate duration. Collection and analysis of current precipitation are also planned in order to learn more about the relation of oxygen-isotope ratios to environmental factors. Progressive changes of oxygen-isotope composition occurring during a single storm will be measured.

Stratigraphic studies of firn should also help in determining the mode and mechanism of accumulation, whether by direct precipitation or wind drifting, and will help define the environmental conditions under which accumulation occurred. The firn stratigrapher may find that useful investigations can be made in the vicinity of rock exposures where possibilities of melting and the incorporation of foreign debris in the section are greatest [*Knowles*, 1945, p. 174]. Although such environments are not representative of the region the fluctuations recorded in them may reflect similar fluctuations in the more representative situations.

The depth at which firn gives way to glacier ice in the Antarctic has been determined accurately only on the shelf ice at Maudheim [*Schytt*, 1956, p. 238], and nothing is known of conditions in the interior. In addition the processes contributing to this transformation in a cold environment need much more study. These problems can be attacked in part by study of cores from shallow hand-drilled holes, but the deep holes will also contribute valuable specimens and more importantly will permit study of changes within the ice below the transformation. The physical aspects of the cored material, such as density, grain size, texture, structure, and related phenomena may reveal features which can be related to variations in the environment. A careful search will be made for ash layers, unconformities, or other stratigraphic markers that might be correlated and possibly dated.

Devotion to a program of stratigraphic investigation should prove fruitful in the Antarctic, but experience in Greenland suggests that the studies must be made with care and in detail at a number of localities before reliable conclusions can be drawn. Pits for stratigraphic work should be at least two meters deep and repeated studies at the same locations over a period of two or more years are desirable.

Thermal regimen—Several independent studies have demonstrated that the temperature in Antarctic firn at a depth of approximately ten meters is the same as the mean annual air temperature [*Wade*, 1945, p. 170; *Loewe*, 1956, p. 663; *Schytt*, 1956, p. 238]. This relation affords a means of determining mean annual air temperature in many parts of Antarctica, and it should be fully exploited by traveling glaciological parties. Certainly it is quicker and easier than establishing and occupying meteorological stations, and the mean annual temperature is a parameter well worth knowing for as much of Antarctica as possible. Hope has been expressed on the basis of theoretical considerations that temperature curves within Antarctic ice will reflect secular climatic variations. Temperature measurements in Greenland (Benson, personal communication) suggest that such is not likely to be the case, for initial differences of temperature within the accumulated firn seem to be rapidly eliminated by conduction.

Glaciers have been classified on a geophysical basis as temperate and polar [*Ahlmann*, 1948, p. 66]. Although the basis for this classification is a matter of discussion [*Court*, in preparation], polar glaciers are supposedly characterized by subfreezing temperatures to a considerable depth and are presumed to have a mantle of frozen firn of unknown thickness. To date, the deepest penetration into polar glaciers is 46 meters in the Greenland ice sheet and 100 meters into an Antarctic Ice Shelf, so direct quantitative data on the above characteristics are limited.

It would be most desirable to know whether or not the pressure-melting temperature is attained at the base of thick polar glaciers, for this has important implications with regard to the amount of basal slip experienced by these bodies and the effects they are likely to have on the underlying rocks. If by any chance the pressure-melting temperature were attained within a depth of 300 meters in the inland ice, this would almost certainly indicate a former climatic environment much warmer than the present. Temperature measurements in 300-meter drill holes will not give all the information needed, but they will constitute a great step forward.

Crystal fabrics—Much work has been done on the crystal fabrics of glacier ice [*Perutz* and *Seligman*, 1939, p. 354; *Rigsby*, 1951; *Bader*, 1951, p. 535; *Demorest*, 1941; 1953, p. 203; *Schwarzacher* and *Untersteiner*, 1953], but interpretations of the results are unsatisfactory. Most fabrics so far recorded are from temperate glaciers and may be the product of recrystallization following flowage. Possibly, recrystallization goes on so much more slowly in cold environments that fabrics preserved in polar ice are more nearly those established by flow. Fecent work in Greenland by Rigsby (personal communication) suggests that this is so, for he has obtained fabric patterns with a strong single maximum corresponding to the theoretical expectation that flow occurs primarily by gliding on the basal crystallographic plane.

For this reason efforts should be made in Antarctica to study fabrics in true glacier ice wherever it is accessible, as for example on bare patches of inland ice denuded by deflation (*Schytt*, 1956, p.

243]. Cores from the deep drill holes will provide unexcelled opportunity to investigate changes in crystallographic orientation occurring through a continuous section of 300 meters from an environment of no deformation to one in which plastic flow presumably occurs. Nearly all earlier studies of crystal fabrics in glacier ice have been made on specimens that arrived at the surface through the relatively slow processes of glacier flow and ablation. It seems more than likely that the fabric of these specimens has been greatly altered during this process and is not wholly representative of crystal orientations established in the ice by flow at depth. Thus, data derived by crystallographic study of fresh cores at intervals through a thickness of 300 meters could constitute a major contribution to the understanding of glacier flow. *Warner* [1945, p. 173] found no recognizable orientation in Antarctic firn to a depth of two meters. The prediction is made on the basis of recent investigations in Greenland by Rigsby (personal communication) that cores from the bottom of the 300-meter hole in the inland ice at least will show a strong crystallographic orientation with basal planes of most ice crystals essentially parallel to the surface slope of the glacier. Confirmation of this prediction would be an exciting and valuable discovery.

Fabric studies should also contribute to an understanding of the constitution and origin of the Ross Ice Shelf by providing one of the best means of identifying the various types of ice composing the body.

Glacier movement—Data on absolute and relative movements, both on the surface and at depth, in Antarctic glaciers, should be obtained. Observations of surface movement by normal surveying procedures are easily made and should record both the vertical and horizontal components. Such studies should involve a network of points rather than a single point or a linear series and should be tied to a fixed base wherever possible. However, fruitful results can be obtained from measurements of relative movements between points on a floating system, as demonstrated by *Schytt* [1956, p. 237] who was able to show by such a study that the ice shelf at Maudheim flows by a spreading out process, possibly akin to extending flow [*Nye*, 1952, p. 86–89]. Extending flow is the type to be expected in most Antarctic glaciers as they lie almost entirely within the zone of accumulation [*Reid*, 1924, p. 604].

Over long periods of time, locations established by celestial observations can be used to record absolute glacier movement, as shown in Greenland by Wallerstein (personal communication). If the South Pole station is reoccupied in five or six years, celestial determination of the site of the old station should give a measure of the direction and rate of flow at the pole. At present little is known about absolute and relative rates of flow of Antarctic glaciers [*Gould*, 1940b, p. 735], and almost any reliable data on this subject will be welcome.

The bore holes will be cased and surveyed periodically by inclinometer to record deformation produced by flowage. Data on differential rates of flow with depth in glaciers are so scarce that every opportunity should be seized to obtain this type of information anywhere in the world. To date, absolutely no data are available from polar glaciers. If at all possible, these holes should be located with respect to fixed points, so that the movement at depth can be related to the total surface movement.

Accumulation and wastage—Some glaciologists are favorably inclined to the thought that the Greenland and Antarctic ice sheets have participated only slightly in the marked shrinkage recently experienced by most other glaciers [*Thorarinsson*, 1940, pp. 147, 152; *Ahlmann*, 1949b, p. 289]. This idea is not firmly based on quantitative data, and a real effort should be made to determine accumulation and wastage at as many points as possible to provide a better estimate of Antarctic glacier regime. Principal interest focuses on the inland ice, of course, but studies on small outlying bodies can be significant as they are more sensitive, easier handled, and may be responding already to changes that will subsequently affect the larger bodies.

Current accumulation is best measured at Antarctic sites with respect to artificial markers, either poles or buried horizontal plates, over intervals of time measured in months or years. Short-period measurements may be significant with respect to individual storms, seasonal variations, or local conditions, but they are likely to be erratic owing to sudden changes between drifting and deflation. With respect to regime, annual accumulation is the important thing, and this can be determined either by identification of annual layers or by measurements as noted above.

Estimates of annual accumulation in the heart of Antarctica are low, on the order of 10–12 cm of water [*Brooks*, 1930, p. 188]. However, *Schytt* [1956, p. 239] measured an average annual accumulation of 36 cm up to an elevation of 2700 meters in Queen Maud Land, and it may be that the amount of accumulation occurring on the Antarctic ice sheet has been underestimated. This possibility should be investigated.

It would be interesting to know at various sites what contribution to accumulation is made by direct precipitation, wind drifting, and condensation in the form of hoar frost. Careful study of the physical characteristic of the accumulated material may provide at least a partial answer. In Terre Adelie essentially all of the accumulated material is said to be wind-drifted, judging from wear on the ice grains [*Loewe*, 1956, p. 658].

Wastage of Antarctic glaciers is primarily by evaporation, deflation, bottom melting, and calving. Surface melting may locally contribute to gross ablation but seldom to net ablation owing to subfreezing temperature in the underlying firn [*Ahlmann*, 1949a, p. 327]. Evaporation, in absolute terms, is probably not large in the Antarctic, and deflation, although locally extremely effective [*Schytt*, 1953, p. 205], influences regime only where material is blown into the sea. *Loewe* [1956, p. 664] calculates that 17×10^9 kilograms of snow per kilometer of coast line are transported by wind into the ocean each year in Terre Adelie. This is a notoriously windy area, and if deflation is assumed to be roughly one-third as effective on the average along the entire coast of Antarctica, the amount of material carried to the sea each year would be equivalent to 5.8×10^{16} cc of water. This amounts to a little less than 0.5 cm of water per each cm^2 of the ice sheet, so wastage by deflation is not a major process. However, quantitative measurements of the amount of material locally transported by wind would be useful. The mechanics of wind transport, and the features of erosion and deposition created by the wind would make good subjects for study by a glaciologist when logistical considerations make other types of work impossible.

Bottom melting of land ice by the heat flux of the Earth is also minor, and the floating ice bodies are small enough so that bottom melting on them, although locally important, does not materially affect the larger picture. This leaves only calving as a possible major process of the wastage for Antarctic glaciers. Nothing is known about the quantitative aspects of this process, and a careful census of the number and volumes of bergs should be kept during IGY to provide a basis for evaluation.

If calving is the major process of wastage in Antarctica, as seems likely, then changes in the environment which affect calving would in turn affect the regime of Antarctic glaciers more than changes affecting other processes of wastage. This is one of several reasons why it will be difficult to predict the response of Antarctic glaciers to specified climatic changes until a better evaluation of factors controlling accumulation and wastage is available.

Considering its size, the items of accumulation and wastage for the Antarctic ice sheet are relatively small, and the basal metabolism of this body is at a low level. Thus, small changes in either accumulation or wastage may produce relatively large effects, but the change is likely to make itself felt slowly because of the size of the body. It may be that sluggishness has been mistaken for balance in earlier estimates of the condition of the inland ice. It would be nice to confirm the guess [*Manley*, 1946, p. 311] that variations in accumulation are much more important than variations in ablation in the regime of the Antarctic ice sheet.

Glaciometeorology—Micrometeorological studies on glaciers show that relations are complex, that generalizations from one area to another are dangerous, and that glaciers are inclined to respond to variations in meteorological factors in subtle and unexpected ways [*Wallèn*, 1948; *Orvig*, 1954; *Hubley*, 1954]. Little is known about the quantitative details of glaciometeorological relations in Antarctica, yet this information is basic to determinations of ancient climatic fluctuations through variations in the size and activity of these glaciers. It has long been popular to think of the Antarctic inland ice as starved by an excessively cold environment and to predict that warmer conditions will produce an expansion [*Gould*, 1940a, p. 868; *Flint*, 1947, p. 51]. This may be correct, but it remains a speculation until our understanding of Antarctic glaciometeorology is advanced beyond its present state [*Ahlmann*, 1949a, p. 330].

Both heat budget and mass budget must be considered in evaluating the state and welfare of these cold polar glaciers. Considerable changes can occur in the heat budget without necessarily affecting the mass budget, and each must be treated separately. In co-operation with activities directed by the United States Meteorological Panel of IGY, measurements will be made of heat transfer across the ice-air interface and of heat changes in the surficial firn layer which will permit determination of the total heat budget of Antarctic glaciers. It has already been shown in Terre Adelie that net radiation at the snow surface is negative [*Loewe*, 1953, p. 249]. Observation of the usual meteorological factors and relations and especially of temperature, humidity, and wind gradients close to the surface at sites where records of accumulation and ablation are kept, should advance our understanding of changes in the mass budget as related to factors of the meteorological environment.

Climatic fluctuations—The relation in time between climatic fluctuations in Antarctica and the rest of the world is important with respect to the basic cause of such fluctuations. The approach to this problem must be largely historical and should involve, as far as possible, major long-time changes, for short-time climatic variations can be notoriously inconsistent from region to region. Climatic fluctuations are recorded by changes in size of Antarctic glaciers, and much evidence has already been cited for an earlier expanded condition of these bodies [*David*, 1914, pp. 622–623; *Gould*, 1940a, p. 863–866; *Taylor*, 1940, pp. 32–33; *Wade* 1937, p. 597; *Flint*, 1947, p. 50; *Manley*, 1946, p. 310; *Ronne*, 1948, p. 266; *Odell*, 1952, p. 51]. Former thicknesses will be determined largely by the geologist using well established criteria such as scoured, polished, and grooved outcrops, erratics, and moraines. 'Trimlines' on lichen-covered rock exposures should not be overlooked. Greater areal extent of the ice will have to be determined largely from submarine topography and glaciomarine sediments [*Ross*, 1937, pp. 577–578].

The objective should be to establish a sequence of events in relative order, and then, more importantly, to date them in an absolute chronology. Carbon^{14} offers the best hope for this, and efforts should be made to find, collect, and establish the proper geological relation of organic materials of significance to the historical sequence and susceptible to analysis. Age determinations from tritium will be too short (30 years) to be of much use, and the recovery of enough entrapped CO_2 from ice to permit a radiocarbon analysis in significant specimens is likely to be difficult.

Hough [1950, p. 258] has shown that sea-bottom cores offer good opportunity for establishing a sequence of events in the history of Antarctic glaciation and possibly for obtaining an absolute as well as a relative chronology. Certainly many submarine cores should be taken and subjected to careful study, for this may prove to be the most reliable and productive approach of all. By extrapolation from such cores, if long enough, a date might be set for the initiation of glaciation in Antarctica about which there has been considerable speculation [*Gould*, 1940b, p. 739; *Manley*, 1946, pp. 311–315].

It should be reiterated that reliable interpretation of climatic fluctuations derived from changes in the size of Antarctic glaciers is dependent upon a better understanding of processes of accumulation and wastage and of glaciometeorological conditions than now exists.

Ross Ice Shelf—More is already known about the Ross Ice Shelf than about any other body of Antarctic ice. Nonetheless, considerable attention will be devoted to it during IGY, partly because it is easily accessible and partly because it is the type specimen of an ice shelf, and such features currently attract considerable interest because of their probable relation to the floating ice islands of the Arctic. Certainly, the constitution, behavior, and origin of the Ross Ice Shelf present fascinating and in good part unsolved problems worthy of attack.

Exceptional opportunity to work on the Ross Ice Shelf will be provided by the location of base stations upon it, by travel across it, and by the simpler logistics involved. It is to be hoped that these favorable aspects will not divert too much attention and effort from the inland ice about which relatively little is known. Wherever the possibility of work in these two environments is a matter of choice, the inland ice should be given the higher priority.

Seismic explorations by *Poulter* [1949] have already defined many of the geometric relations of the Ross Ice Shelf, and further seismic, gravity, and geodetic measurements during IGY will extend this knowledge. Data will be obtained on thickness, areas where the shelf is aground, depth of underlying water, and possibly the thickness of unconsolidated deposits on the sea bottom.

Marshall's [1955] stratigraphic investigations by means of pits and cored drill holes on the Ellesmere Ice Shelf have contributed to an understanding of the constitution, history, and origin of that feature. A similar investigation is projected for the Ross Ice Shelf and promises to yield useful information on the amount and geographic variation of surface accumulation, the present and past regime, temperature conditions, constitution, historical events, and genesis. Marshall (personal communication) also proposes to study solid particles included in the snow and firn of the Ross Ice Shelf which will be collected by a process of microfiltration.

Temperature measurements in the projected deep drill hole and study of cores therefrom should provide critical information pertinent to the problem of bottom melting versus bottom accretion on the Ross Ice Shelf, a still much debated topic [*Debenham*, 1948, pp. 204–208; *Gould*, 1935, pp. 1388–1390; *Wade*, 1945, p. 162; *Schytt*, 1956, pp. 237–238). If the lower part of the shelf consists of frozen sea water, cores from deep drill holes should show this, although one would still be faced with the task of distinguishing between pack ice and accretion ice, but this too might be possible.

Careful vertical control of surface survey points should give a measure of the magnitude of bottom melting, for the essentially constant surface elevations recorded on ice shelves in the face of measurable accumulation suggest that bottom melting occurs in an amount equivalent to the accumulation [*Wade*, 1945, p. 162; *Odell*, 1952, p. 41; *Schytt*, 1956, pp. 237–238].

Measurement of deformation within the deep drill hole should give an indication as to the type of flow occurring in this floating ice sheet. Careful surveys of networks of surface points should also be made in order to check and extend *Schytt's* [1956, p. 237] demonstration of spreading or extending flow [*Nye*, 1952, pp. 86–89] in shelf ice. This is an idea long advocated [*Wright*, 1925, p. 201] but without supporting data. It would be interesting to see if the direction and velocity of flow in the Ross Ice Shelf show any relation to the direction and degree of surface slope. This could be ascertained by field surveys.

A thorough investigation is planned of the various structures within the Ross Ice Shelf such as rolls, folds, crevasses, and hinge lines. The folds and crevasses are particularly worthy of study because their interpretation, in terms of a solid but presumably 'plastic' crust floating on a fluid and being deformed under a defined stress system, can be highly significant from the viewpoint of structural geology.

The existence of well established bases on the Ross Ice Shelf will give opportunity for detailed local studies of the processes of firnification, crystal growth, crystal fabrics, compaction rates [*Wade*, 1945, p. 162–167; *Howard*, 1948, p. 921; *Schytt*, 1956, p. 241] and other relations of basic interest to glaciology.

Concluding generalities—Scientists are being put into the Antarctic at great expense and effort. They are the first team, the featured performers, so to speak, with a large supporting cast. Under such circumstances each scientist has an obligation to make the best possible use of his time and opportunities.

A plea has already been made for a definitive and focused program of glaciological investigation, but there will be countless occasions when circumstances will combine to keep the glaciologist from pursuing this program. Under such conditions he must be mentally adjusted to seek out and follow other lines of investigation. He will be on the greatest untouched glaciological frontier on Earth and it is inconceivable that the alert glaciologist cannot find some program of study in almost every situation and at almost any place in Antarctica which will produce useful results. The vigorous, imaginative glaciologist with initiative should have few idle moments in Antarctica.

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Antarctic Climatology and Meteorology

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Abstract—The Antarctic affords an opportunity to investigate a wide range of meteorological problems under conditions not found elsewhere on Earth. These problems include the examination of the thermal, mass, and mobile structure of an atmosphere cut off both from direct solar energy for many months and, in contrast to its Arctic Ocean counterpart, from conduction of appreciable heat from below. The sharp distinction between the troposphere and the stratosphere, so marked elsewhere, is believed to vanish during the polar night over Antarctica.

Another problem is whether the Antarctic troposphere's flow pattern is dominated by the mid-latitude planetary wave system moving like spokes of a wheel around the Pole as appears to be the case in the Arctic, or by waves moving radially outward from the interior of the Continent, as suggested by earlier meteorological observations. A smaller-scale, but important problem, especially for field and aircraft parties, is the drainage, blocking, and deflective influence of mountains and hills on producing local circulations and blizzardy winds up to hurricane force.

The existence of a uniformly thermal and flat snow surface, such as is found for hundreds of miles over the Ross Ice Shelf, will provide an unexcelled natural laboratory to study atmospheric turbulence and energy exchange between atmosphere and snow surface. The incoming and outgoing radiation fluxes, the albedo of the snow surface, the polar white-out, and the variations of ozone and other gases are further examples of problems in polar geophysics which will be investigated during the forthcoming International Geophysical Year.

Kidson [1932], discussing problems of Antarctic meteorology, said "... it would not appear from the amount of energy devoted in the Second Polar Year scheme to the Antarctic that its problems weighed heavily on the consciences of the world's meteorologists." After looking into the plans for greatly expanded meteorological activities in the Antarctic during the International Geophysical Year, one cannot help coming to the conclusion that our consciences have been bothering us ever since 1932.

Much of our previous 'lack of conscience' at the time of the last Polar Year was not that, really. It was more related to a lack of knowledge of the Southern Hemisphere in general, and of Antarctica, in particular. This was due, mainly, to the restrictions imposed by the existence of vast uninhabited regions, in the first case, and to the extreme living conditions, in the second. Previous scientific expeditions were rarely contemporaneous, and were widely scattered around the periphery of the continent; situations which have resulted, sometimes, in conflicting climatological and meteorological impressions. There was a reasonable knowledge of weather processes in some regions of the Southern Hemisphere, but little had been done to coordinate this information; indeed, there was little to coordinate. In recent years, however, progress has been made in the direction of more adequately describing the Southern Hemisphere circulation by construction of daily Southern Hemisphere weather charts [*Rubin*, 1952; *van Rooy*, 1952]. This progress has led, inevitably, to more interest in the Antarctic regions, whose influence has to be taken into account in any unified concept of the general circulation.

Our lack of a unified concept of the Antarctic atmospheric circulation, and our desire to fill this need, is best typified by a statement by *Court* [1951]. He said, "for the first time in history, prospects are bright that a good understanding of Antarctica's atmospheric circulation, and thus its climate, can be achieved in the near future." This was not a prophetic reference to the present IGY activities, but was occasioned by the establishment of meteorological stations on a number of sub-Antarctic islands, at Maudheim and Port Martin, and in the Palmer Peninsula region. Court pointed out the need for year-round stations in the interior of the continent. This requirement will be fulfilled during the IGY.

Until now we have had any number of partially or wholly conflicting theories concerning the Antarctic atmospheric circulation [*Court*, 1951; *Lamb* and *Britton*, 1955]. The reason for this is obvious; there have not been enough observations, either in time or in space. This is especially true as regards upper-air observations. Basic solar-radiation data, humidity values, and even air temperatures are unknown over most of the continent. One can list a host of fundamental meteorological questions which remain unanswered due to lack of basic data from Antarctica. It is of importance to our attempts to understand the atmospheric processes of the Earth that we be able to make a reasonably accurate estimate of the role played by Antarctica and its atmosphere. Does it take an active part in the general circulation, or is it for the most part sealed off from the rest of the atmosphere? Are the strong west winds, which are caused by the unique juxtaposition of the polar continent and the warm surrounding oceans, a barrier to the meridional exchange processes which are normal in the middle and high latitudes of the Northern Hemisphere? Are the circumpolar long-waves in the westerlies an important influence in Antarctica, or are pressure waves radiating from Antarctica a factor of significance in the general circulation? Is the geographical South Pole also the South Pole of the atmospheric circulation? In what directions and at what levels are heat, mass, moisture, and momentum transported? What is the effect of a lesser seasonal variation of temperature over the oceans, as compared to the continent, in terms of the surface and upper-air wind movements? How does the atmosphere operate to achieve a near zero heat balance during particular seasons? Where and when is precipitation deposited, and how are we to measure it so as to distinguish between falling and drifting snow? How is the weather related to solar influences such as sunspot activity, variations in ultra-violet, or sudden ionospheric disturbances? Are there significant variations in the electrical field or chemical composition of the atmosphere which can be related to weather and climate? One can go on all day long posing problems. It will be years before some are answered; but to borrow some of Court's optimism of 1951, in 1956 we can look forward to answers to many of these problems within the near future.

None of the above questions has been answered in more than a gross way until now. That the Antarctic regions are cold we have known ever since Captain Cook's voyages of the period 1772 to 1775. But how cold they are, we still do not know today. At Bolling Advance Base the minimum temperature was −61°C. The men who will be wintering over at the interior stations can be expected to make meteorological history. The construction of climatic charts will be aided by the fact that below about 20 meters the ice temperatures correspond closely to the local mean air temperatures. From rawinsonde observations it will be possible to analyze the wind currents from day to day, and to fit the large-scale features of the Antarctic circulation into the patterns of the general atmospheric circulation, as determined by observations from other parts of the hemisphere.

The particular interest which Antarctica has for us is, of course, the unique opportunity it affords to study meteorological conditions over a large region which is perpetually ice-covered—literally in an ice-age. Being able to make measurements of continental influences during the long polar night will provide valuable comparisons with the Arctic, which differs in that appreciable amounts of heat are transported through the relatively thin ice covering the Arctic ocean, giving the higher surface temperatures observed there. This difference in the two polar regions is thought also to account for the so-called disappearance of the tropopause during the Antarctic winter, as shown at Little America in 1939–41 [*Court*, 1942], and ten years later at Maudheim [*Schumacher*, 1955] on the other side of the continent (Fig. 1). Estimates of the rate of radiative cooling during the Antarctic winter seem to indicate that it can account for the observed minimum temperatures of the order of −90°C attained in the Antarctic stratosphere during the late winter, and the so-called disappearance of the tropopause [*Rubin*, 1953]. We have not seen the Port Martin reports from Adelie Land, but information indicates that the tropopause disappearance is rarely observed there [*Expeditions Polaires Francaise*, 1951–1953].

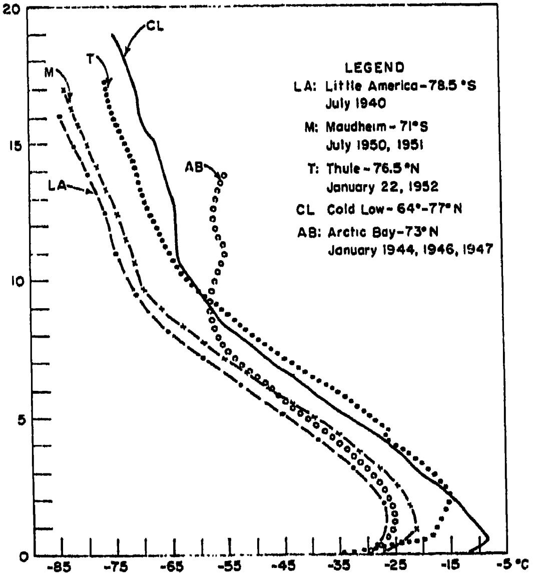

Fig. 1 – Mean and individual wintertime temperature soundings, illustrating the phenomenon of a 'disappearing' tropopause

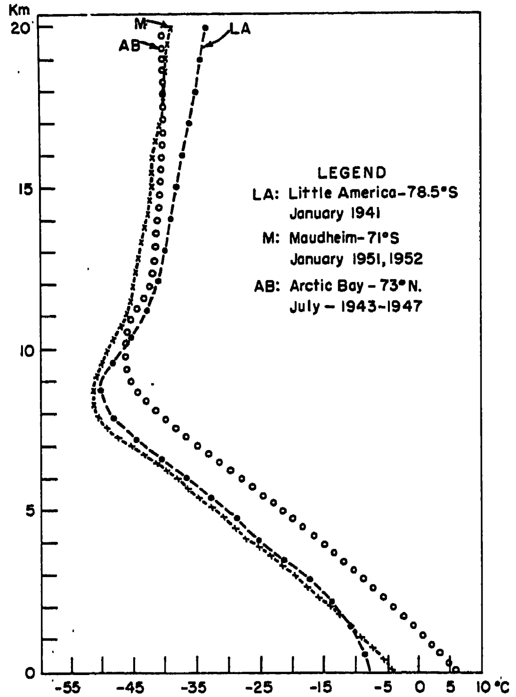

FIG. 2 – Mean summertime temperature soundings from two Antarctic and one Arctic station

A latitude difference may account for this, as Port Martin is at 67°S, as compared to 71° for Maudheim and 78° for Little America. In this connection we may say that, in recent studies of the Northern Hemisphere 50 and 100-mb levels, which are approximately 20 and 16 km, respectively, above sea level, there has been brought out the fact that individual soundings (cf. Thule) in the lower stratosphere of the Arctic regions at times approach the very low temperatures reported from both Little America and Maudheim (Fig. 1). However, the mean wintertime temperature from any Arctic station (cf. Arctic Bay) is not comparably low; nor are those temperatures measured in the cold high level lows. The sounding in Figure 1 labelled CL represents the mean of ten soundings reaching the level of 15 km in the cold southwest quadrant of stratospheric (50 mb) cyclones as they moved around in the polar regions between 64° and 77°N during January and February 1953. This brings out a significant thought as regards the basic difference between the Arctic and Antarctic regions. The Arctic cold lows may move often enough from their preferred positions so that soundings at fixed places are never as cold as those made all the time in cold stratospheric lows. On the other hand, on the basis of the temperature data from Little America and Maudheim, one can conceive of one, or perhaps two relatively permanent deep, cold stratospheric lows over those regions of Antarctica during the winter season. This basic difference has significant connotations as regards the general circulation patterns of the two hemispheres.

In contrast to the condition of late wintertime extreme cold in the lower stratosphere in Antarctica, we find that the *maximum* temperatures at 20 km in the Antarctic stratosphere in summer are of the order of 10°C higher than in the Arctic regions [*Rubin*, 1953]. The *mean* soundings from Little America and Arctic Bay (Fig. 2) show a lesser temperature difference in the stratosphere, of the order of 5 to 10°C. Those from Maudheim are from 2 to 6°C lower than Little America everywhere in the stratosphere from 10 to 20 km. A possible maximum instrumental error of as much as 5°C due to radiation in the Little America data would make the soundings more comparable, but with the possibility that the Antarctic stratosphere is slightly warmer.

This question is one which will be answered when we have available simultaneous and comparable data from both regions during the IGY. The warming from the wintertime minima appears to take place first at the higher levels, progressing downward from spring to summer, indicating direct absorption of solar radiation, presumably by ozone. The high- and low-level winds around Antarctica must be greatly influenced by the contrast between the cold continent and the relatively warm oceans at all seasons of the year. The tropospheric flow patterns have not yet been delineated definitely in the Southern Hemisphere. However, it appears that the flow pattern is mainly zonal throughout the year, with the possibility that a broadening of the westerly circulation takes place during the winter season. There is a tendency for from three to five long-wave systems to exist around the hemisphere in the mid-troposphere. In the mean, these waves may not move appreciably from their preferred positions.

Figure 3 is a schematic diagram showing some prominent features of the Southern Hemisphere circulation in summer. It is based mainly upon mean maps very kindly supplied by Vowinckel and van Loon of the South African Weather Bureau. Of course, there are breakdowns in this pattern from time to time [*Rubin* and *van Loon*, 1954], and polar air has been known to reach quite low latitudes over Africa, South America, and in the Australia-New Zealand sector. Blocking patterns, which interfere with zonal movements similar to those in the Northern Hemisphere,

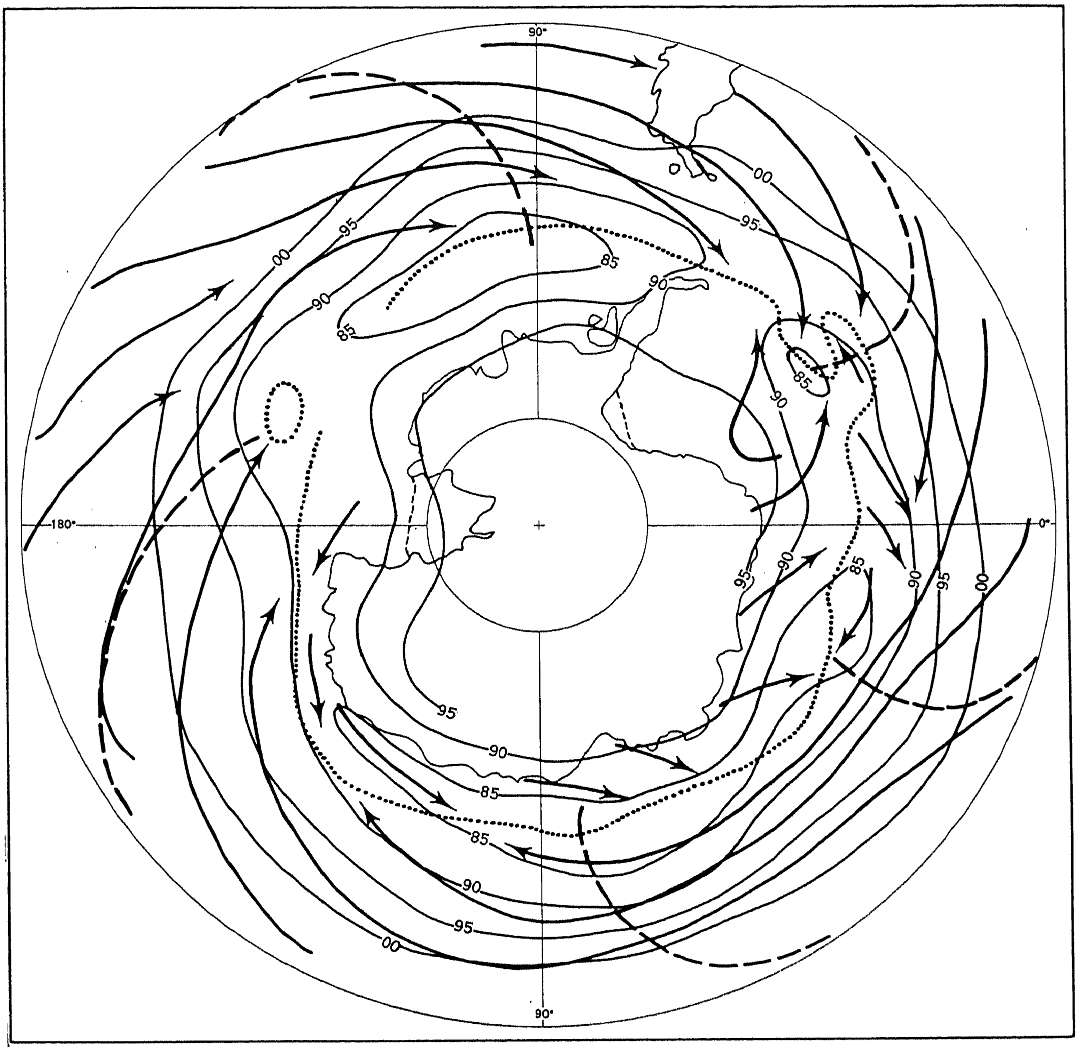

FIG. 3 – Schematic features of the Southern Hemisphere circulation in summer, with mean January sea-level isobars at and below 1000 mb; arrows show general surface wind flow; solid thin lines are sea-level isobars (mb); dotted lines separate westerly flow from easterly; dashed lines depict relative positions of mid-tropospheric long-wave troughs when five such troughs exist

become evident, and deep southerly streams of air persist for days on end. Whether the major influence in this regard comes from the variations of the westerlies, or from prior variations in the Antarctic circulation, we cannot yet say. Pressure waves from the interior of the continent are thought by some to be an important factor. To show that we have not progressed very far in this direction, we refer to a comment by *Arctowski* [1905], made in 1904, and almost as valid today as it was then,

> "The thing desired is to have as great a number of stations as possible working, all simultaneously, not only with a view of accumulating the data resulting from the ordinary hourly meteorological observations, but, first of all, with a view of enriching our knowledge of the meteorological conditions of the upper regions of the atmosphere. . . ."
>
> "The stations must be sufficiently near one another to permit, after the return of the expeditions, the drawing of daily synoptic maps—or even hourly, for the most interesting cases—and it is only under such conditions that we shall succeed in learning the usual tracks of the cyclones which are observed in the sub-antarctic regions all around the polar ice cap, and about the movements of which we have no knowledge, for we do not even know whether they converge toward the pole, following a spiral track, or whether, on the contrary, the depressions are formed on the borders of the ice (where the isotherms are very close together) and, leaving the polar circle, pass northwestward."

And Arctowski goes on to say

> "If all the expeditions . . . had wintered over simultaneously and if they had been seconded by stations . . . on the subantarctic islands, the discussion of the whole of the observations would possibly have revealed not only the exact position of the isotherms and of the isobars all around the south polar ice cap, but also the course of the tempests and perhaps, even, the laws of the general circulation of the atmosphere in Antarctica; whereas, on the contrary, because of the conditions in which the several winterings were made, we shall have only climatological data and a series of questions simply touched upon but not resolved in everything concerning the dynamics of the atmosphere."

The particular locations of several of the stations in the interior were suggested to help, when related to the coastal observations, clear up the question of storm tracks, pressure waves, and so forth.

From one synoptic study [*Rubin* and *van Loon*, 1954] which was made in the past few years, it appears that some polar outbreaks can completely disrupt the circulation in the middle latitudes. Also, it appears that weather conditions in the Antarctic, at least in the Ross Sea, are related to the flow patterns existing over New Zealand. During the recent operations which established the United States IGY stations in Antarctica, there was opportunity to obtain data from a north-south section. This information has influenced our thinking about the circulation in that region. In the mean surface pressure maps for November and December, 1955, prepared by the New Zealand Meteorological Office and reproduced in Figure 4, we see an example of a great change from the usual zonal pattern to a strong and persistent blocking pattern over and south of New Zealand. This blocking situation which persisted, with slight breaks, for a month or more, is shown in the mean pressure map for December. It persisted and also affected the pattern for January, 1956. The blocking was associated with strong southerly winds, relatively clear skies over the plateau, a displacement of the storm path, and breaking up of bay

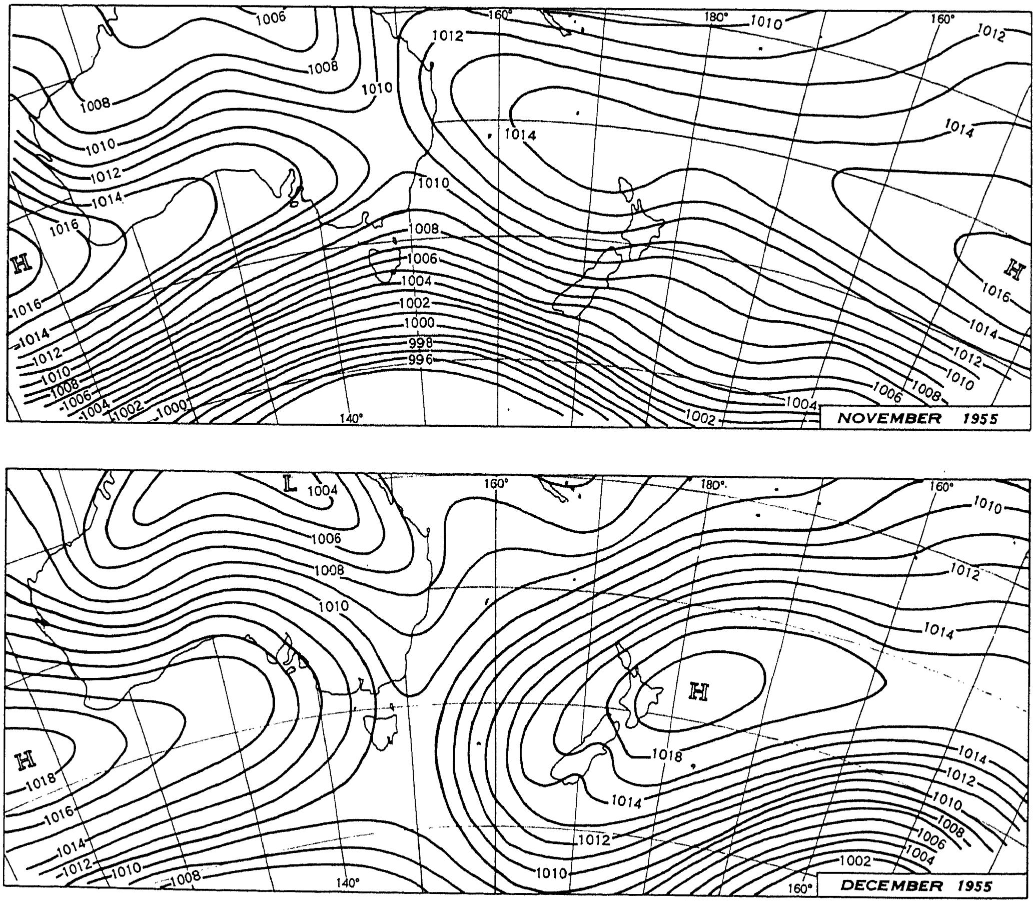

FIG. 4 – November and December 1955 mean surface pressure maps over and around New Zealand, prepared by New Zealand Meteorological Office

ice in many regions. Any disturbances seemed to be confined to the lower atmosphere, perhaps associated with the large and permanent temperature contrast between continent and ocean. The extent to which the blocking pattern influences continental weather, and if such patterns are normal, has great climatological significance. There is evidence that the predominant air movement at the surface is an outflow from the continent. But variations in speed and direction are likely to be significant, both in space and time. Longer records from the old stations, and new records from other sites will help in putting together what is now a patchwork quilt of data from different times and places.

In examining the data from the past and from the contemporary stations on the continent, one can see quite striking differences in climate. Whether large-scale or local influences are more important in bringing about these differences is not yet known. Places as far apart as Maudheim and Little America have similar wind and temperature characteristics, and have quite different wind regimes from Cape Denison, Port Martin, and Cape Adare (Table 1). Siple has quoted the suggestion of *Lamb* and *Britton* [1955] that the cause of the very strong persistent winds at Port Martin and Cape Denison (about 30 miles east of Port Martin) may be the existence of a geographical 'slot', which channels the drainage winds from the plateau. The lesser wind speeds at Point Geologie, which is almost 30 miles west of Port Martin, may be explained by local obstacles such as the Terra Nova glacier. On the other hand, the reported existence of a tropopause at Port Martin [*Expeditions Polaires Francaise*, 1951–1953] during the winter, as contrasted to its disappearance at Little America and Maudheim may be related to the movement of air from lower latitudes. The analysis of the large-scale motions of the Earth's atmosphere in the Southern Hemisphere during the IGY may help to clear up this question. A detailed study of the IGY data in relation to topography and synoptic weather patterns will also throw more light on the question of local winds, which assumes great importance in Antarctic operations.

TABLE 1 – *Mean wind speeds by month and year from several Antarctic stations; numbers following station names refer to the year or years of observations; for example, Cape Denison 1912/1913* [*Grimminger, 1941; Court, 1949; Robin, 1953; Loewe, 1954; Simpson, 1919, 1923*]

Station	Mean wind speed, knots												
	J	F	M	A	M	J	J	A	S	O	N	D	Year
Cape Denison 12/13	25	27	41	41	45	43	47	43	37	43	33	31	38
Port Martin 51	25	27	56	47	35	33	43	39	35	31	35	25	36
Maudheim 50/51	15	17	12	16	15	14	16	16	16	15	14	11	15
Little America 34	10	11	12	12	10	10	10	8	10	12	10	8	10
Bolling Advance Base 34	...	...	...	8	6	8	7	6	7	...	...	...	...
Little America, three years	9	10	12	10	9	11	9	9	9	10	9	8	10
Cape Adare 11	...	...	8	6	14	3	2	6	12	4	4	6	6
Hut Point-C. Evans, four years	8	14	16	12	14	15	15	15	13	12	12	9	13

Winds on the polar plateau are known only in summer, and for short periods only. They are known to be predominantly from the south, and mainly light in force although surface winds of Beaufort force 8 (34–40 knots) have been experienced. The Bolling Advance Base on the shelf ice only about 100 miles south of Little America, which was occupied by Admiral Byrd for 200 days in 1934, at times showed significant differences from Little America's winds. A comparison of upper-air winds from Mawson and the Russian station, Mirny, located about 700 miles eastward, for a short time during this past Antarctic summer (January, 1956) show up to 90° difference in the wind direction [*South African Weather Bureau*, 1956], indicating perhaps a large-scale cyclonic circulation in that region. This circulation may not be typical, and it does not bear out other impressions which we have had on the basis of surface data over a period of years.

Until now we have had little information concerning energy exchanges between the snow surface and the atmosphere in Antarctica. Much will be done in this connection during the IGY. Preliminary reports of the Norwegian-British-Swedish Maudheim observations have been published [*Liljequist*, 1953]. Liljequist found that the effective solar radiation remains, essentially, at that which is received on clear and cloudless days, even when as much as 20 pct of the sky is covered by clouds. The screening effect of clouds is seemingly compensated for by a higher diffuse radiation. With overcast skies in spring the albedo was found to be 85–90 pct; in summer 80–90 pct; and in autumn 85–90 pct. After recrystallization of the snow into larger grains in summer, and after snowfalls of large crystals, a lowering of albedo to 70–80 pct was noted. When crystals were broken up by strong winds, the albedo value rose to 90 pct. Liljequist found that the reflective properties of the snow surface are complicated, depending upon the state of the surface, the size of the snow grains, the angle of incidence, and the spectral composition of the radiation. The direct solar radiation in summer exceeded the high value of

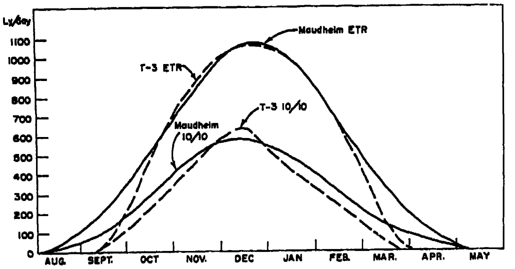

FIG. 5 – Theoretical values (ly/day) of extra-terrestrial radiation (ETR) received at Maudheim (71°S) and T-3 Ice Island (>85°N), and actual values (ly/day) during conditions of overcast skies; Northern Hemisphere values displaced by six months for direct comparison (after Fritz)

1.5 ly/min, or 75 pct of the solar constant. (A langley is a unit of energy equal to one calorie per square centimeter.) Even overcast skies did not cut down the insolation greatly; in spring with thin clouds, the insolation with overcast sky was up to 70 pct of the clear sky insolation. In summer and autumn these values varied between 55 and 60 pct. This is compared with temperate region values of about 29 pct. A comparison of Maudheim and the T-3 Ice Island radiation data is of interest (Fig. 5). T-3 was north of 85°N, and Maudheim is at 71°S; however, for the period of the year with comparable solar elevation corresponding to the Northern Hemisphere period from mid-April to mid-August, the computed values of extraterrestrial radiation in ly/day are almost exactly equal, according to computations kindly supplied by S. Fritz of the U. S. Weather Bureau. Considering days with overcast skies only, as this was mainly the situation at T-3, Maudheim has consistently higher values, except for the month of June. This difference is probably related to differences in cloud thickness, albedo, and transmission characteristics of the atmosphere.

With clear skies and a small temperature gradient in the lowest few decameters, Liljequist found high effective outgoing radiation, about 0.1 ly/min. As temperature inversions developed, with moderate to light winds, the values tended to decrease gradually and to become stable at 0.04 to 0.05 ly/min, which is about 1/4 to 1/3 of Arctic values computed by Sverdrup on the *Maud* Expedition. In winter, if the sky clouds over, the outgoing radiation is changed temporarily to incoming 'black-body' radiation. Values up to 0.045 ly/min were observed, and can bring a temperature rise of 15–20°C within a few hours. This may not be entirely due to radiation from the relatively warm clouds. Advection may be a factor and its role, relative to radiation, will be studied when additional data become available. In general, Liljequist thinks that net radiation values, plus or minus, are small over the snow surface, most of the time. In summer this condition is due mainly to the high albedo of the snow surface; in winter it is due to the development of surface inversions which protect the snow surface from heavy radiative energy losses.

Obervations of sky brightness, which are part of a planned program of radiation measurements, may throw some light on the problem of polar white-out. Ordinarily, with no snow cover, the zenith sky will have three times the brightness of the horizon sky. With a snow cover, the overall sky-brightness increases, and theory suggests that the difference between zenith and horizon brightness decreases. The white-out condition is one in which, among other features, there is no apparent difference between the horizon and zenith brightness; and this may be related to surface albedo values. The sky-brightness measurements will be made in an attempt to relate zenith brightness to horizon brightness for the various surface albedo values encountered.

Measurements of oxygen, carbon dioxide, and precipitation-chemical elements will be helpful in bringing about a better understanding of atmospheric processes. The apparent oxygen deficiency noted at Little America in 1940 [*Court*, 1942], of the order of 0.2 pct in winter and 0.4 pct in summer, has not been substantiated by recent observations taken during the *Atka* expedition of 1954–1955; although slightly lower values (20.85 pct by volume) than the normal (20.95 pct) were noted. Measurements of CO_2 on the *Atka* showed wide variations, but are much lower than earlier determinations. This variation, if real, can have great significance when related to synoptic circulation patterns. A continuous CO_2 infrared recorder to be installed at Little America should furnish substantiating data.

Particular emphasis will be given to the measurement of atmospheric ozone. A continuous chemical record of the surface ozone content will be maintained at the Little America base, and perhaps at other stations. The total ozone content in the vertical column will be measured by the Dobson spectrophotometer, using the Sun as a source during the day, and the Moon during the night. Since ozone is formed 20 to 30 miles high in the atmosphere, only by the action of the solar ultraviolet radiations, its detection during the Antarctic night will indicate that exchange of air with lower latitudes takes place. The presence of appreciable ozone in the surface air in Antarctica during the winter night will imply not only the existence of considerable horizontal advection of air from the north, but vertical sinking as well.

The establishment of observing stations in a meteorologically unknown region is always an exciting event; but to do so in an area as large as Antarctica, with its extremes of radiation, temperature, pressure, and wind, will represent an historic achievement in the exploration of the atmosphere of the planet Earth.

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Antarctic Stratigraphy and Structure

William E. Davies

Abstract—Antarctica is divisible geographically and geologically into two distinct regions. West Antarctica, that portion lying south of the Americas, consists of folded ranges and plateaus with sediments deposited in Mesozoic and Tertiary geosynclines. These sediments along with the intrusives that invade them are of the Andean type and are traceable from Antarctica through the subantarctic islands of the Scotia Arc to South America.

East Antarctica, lying south of Australia and Africa, is a continental shield. In this area is a Precambrian basement of schists, gneisses and intrusives overlain by a thick series of Paleozoic and Mesozoic sediments. The sediments are horizontal, and are thickest along the south and west sides of the Ross Sea. They have been intruded by numerous sills and dikes. Along the Antarctic coasts south of Australia and the Indian Ocean the basement rocks form most of the ice-free areas with the sediments apparently confined to the higher plateaus in the interior of the continent.

Along Palmer Peninsula in West Antarctica is a cordillera belt of multiple chains of folds which fan out into widely spaced arcs in the continental mass to the south. The shield in East Antarctica is bounded by a series of horst blocks along the Ross Sea and the Ross Ice Shelf. Inland from the horst is a high ice-covered plateau with the sediments gently dipping away from the horst.

Tertiary and recent volcanoes of the 'Atlantic type' lie along the edge of the Antarctic shield while those of the 'circum-Pacific type' are developed along the outer folds on the Palmer Peninsula in West Antarctica.

From practical experience one might conclude that the ease of formulating broad, general concepts of the geology of an area varies inversely with the amount of data on hand. Such is definitely the case in the Antarctic where data are so meager and field investigations so few and far between.

The first geological observations on the Antarctic were made over a century ago on the islands lying off the Palmer Peninsula, but it was not until 1894 that the first rock samples from the continent were collected. The first detailed geological investigations were made by C. E. Borchgrevink in 1899 and 1900 and the first geologic map based on field surveys of a part of the continent was published in 1906 by J. Gunnar Andersson of the Swedish Antarctic Expedition of 1901–03. At present geologic data from field surveys are available for much of the Palmer Peninsula and the adjacent islands, in the Edsel Ford Ranges and Rockefeller Mountains of Marie Byrd Land, the Queen Maud Mountains, and the Royal Society Range in South Victoria Land (Fig. 1). In the remainder of Antarctica geologic investigations have been made at a number of points along the coast but detailed information is available only from Cape Adare, King George V Coast, Queen Mary Coast, and Princess Martha Coast.

For ease of discussion the Antarctic can be separated into two geological entities (Table 1). That part of the Continent lying south of the Americas constitutes a unit that is referred to as West Antarctica, and that part south of Australia, Africa, and the Indian Ocean is East Antarctica. From a geologic viewpoint these areas are extreme contrasts. East Antarctica consists of a high plateau forming a shield area; West Antarctica is an area of Mesozoic and Tertiary folded rocks (Fig. 2). The shield consists of an elevated basement complex overlain by a thick series of clastic sedimentary rocks and included sills and dikes of diabase. The sedimentary rocks have been studied in South Victoria Land and the Queen Maud Mountains and the basement complex has been investigated at a number of points along the periphery of the Continent from the Ross Sea westward to the Weddell Sea. The folded rocks of West Antarctica consist of a series of folded Mesozoic and Tertiary clastic sedimentary rocks overlying a basement of Andean-type intrusives and metamorphics.

For the sake of simplicity the geology of East Antarctica will be discussed first. Information on this area is based mainly on field surveys of three British expeditions of Victoria Land, Byrd's expeditions in the Queen Maud Range, Australian, French, German, and American expeditions in Wilkes Land, and the British-Norwegian-Swedish Expedition in the vicinity of Princess Martha Coast (Fig. 1).

East Antarctica is a stable shield consisting of a basement complex overlain by a thick series of

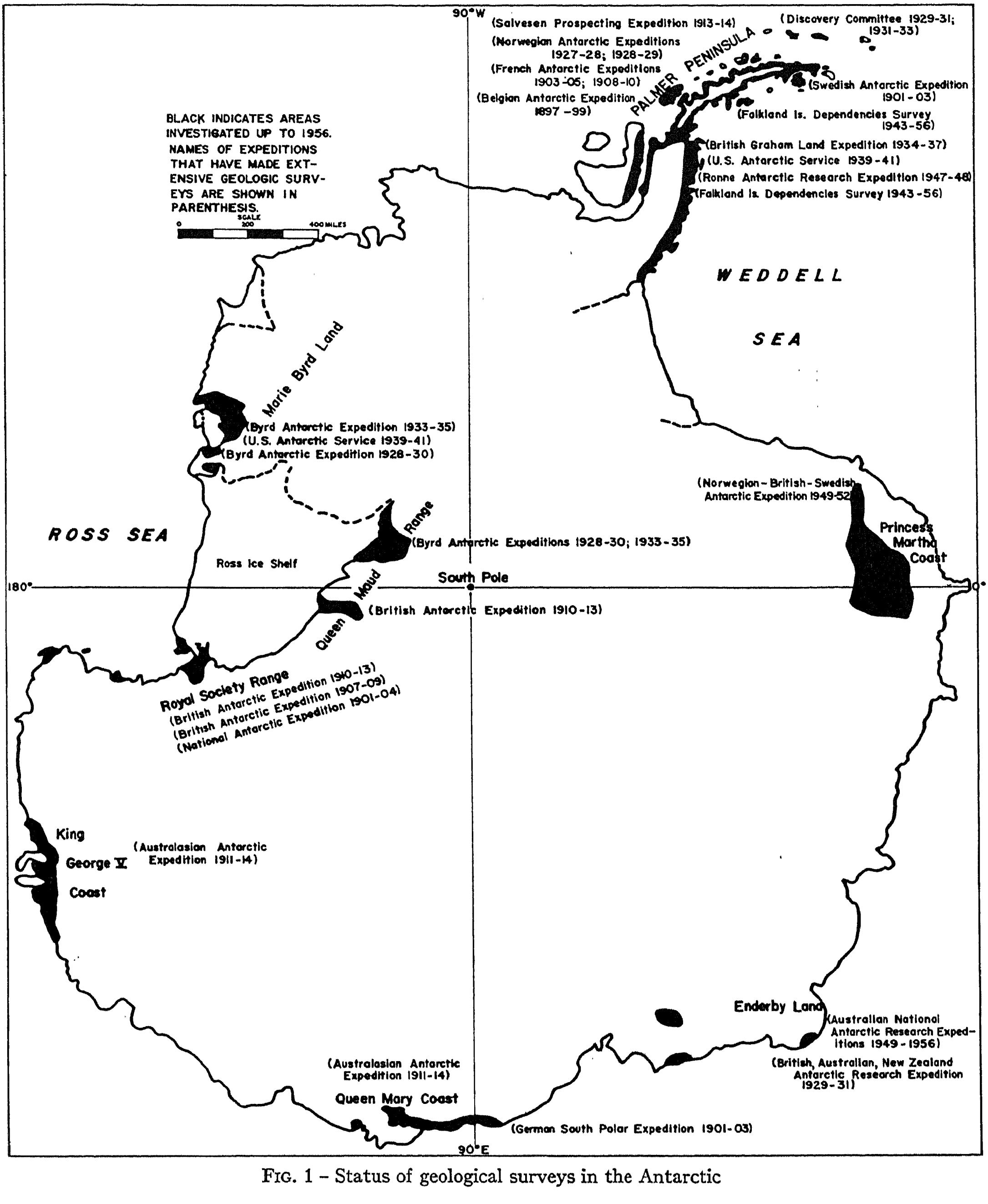
90°W
(Salvesen Prospecting Expedition 1913-14)
(Norwegian Antarctic Expeditions 1927-28; 1928-29)
(French Antarctic Expeditions 1903-05; 1908-10)
(Belgian Antarctic Expedition 1897-99)
PALMER PENINSULA
(Discovery Committee 1929-31; 1931-33)
(Swedish Antarctic Expedition 1901-03)
(Falkland Is. Dependencies Survey 1943-56)
(British Graham Land Expedition 1934-37)
(U.S. Antarctic Service 1939-41)
(Ronne Antarctic Research Expedition 1947-48)
(Falkland Is. Dependencies Survey 1943-56)
BLACK INDICATES AREAS INVESTIGATED UP TO 1956. NAMES OF EXPEDITIONS THAT HAVE MADE EXTENSIVE GEOLOGIC SURVEYS ARE SHOWN IN PARENTHESIS.
SCALE
0
200
400 MILES
WEDDELL SEA
Marie Byrd Land
(Byrd Antarctic Expedition 1933-35)
(U.S. Antarctic Service 1939-41)
(Byrd Antarctic Expedition 1928-30)
(Norwegian-British-Swedish Antarctic Expedition 1949-52)
Princess Martha Coast
ROSS SEA
Ross Ice Shelf
Queen Maud Range
(Byrd Antarctic Expeditions 1928-30; 1933-35)
South Pole
180°
0°
(British Antarctic Expedition 1910-13)
Royal Society Range
(British Antarctic Expedition 1910-13)
(British Antarctic Expedition 1907-09)
(National Antarctic Expedition 1901-04)
King George V Coast
(Australasian Antarctic Expedition 1911-14)
Enderby Land
(Australian National Antarctic Research Expeditions 1949-1956)
(British, Australian, New Zealand Antarctic Research Expedition 1929-31)
(Australasian Antarctic Expedition 1911-14)
Queen Mary Coast
(German South Polar Expedition 1901-03)
90°E

FIG. 1 – Status of geological surveys in the Antarctic

Paleozoic to early Mesozoic sedimentary rocks (Fig. 3). The basement rocks in Victoria Land along the Ross Sea are primarily granite and a great variety of metamorphosed igneous and sedimentary rocks that are believed to be Precambrian in age. The metamorphic rocks are dominantly granite gneisses associated with a belt of crystalline limestone. The gneisses are mainly gray biotite gneisses, some of which are garnetiferous. Included with the gneisses are several types of fine-grained granulites, muscovite-biotite schist, and graphitic mica schists.

The crystalline limestones are apparently widespread in the metamorphic complex around the McMurdo area. The limestones are coarsely crystalline and generally pure white to gray in color. They are relatively pure, although some are rich in chondrodite and spinel. On weathering the lime-

TABLE 1 – *Comparative geology of West and East Antarctica*

System or series	West Antarctica		East Antarctica		
	Palmer Peninsula	Marie Byrd Land	Ross Sea	Wilkes Land	Princess Martha Coast
Recent	Moraines and volcanic rocks	Moraines and olivine basalt	Moraines and kenyte-type lava	Moraines and leucite basalt	Moraines ...
Upper Tertiary	So-called 'Pecten' conglomerate	...	Trachyte	...	...
Eocene and Miocene	Seymour Island group (Continental in lower part; marine in upper part)	...	...	...	...
Cretaceous	Snow Hill group	Granite and granodiorite ?	Diabase	...	Diabase ?
Jurassic	Volcanic rocks and sedimentary rocks with plant fossils	Metasedimentary and plutonic rocks	...	...	...
Triassic	...		Beacon group Upper sandstone with diabase	...	...
Carboniferous Systems	...		Coal beds	...	...
Devonian	...		Lower sandstone	...	Altered andesitic lava; graywacke and metasedimentary rocks
Silurian	...		Robertson Bay group?	...	
Ordovician	Graywacke and phyllite with graptolites			...	
Cambrian	...		Limestone	...	
Precambrian	Schist	Schist and gneiss	Granite, schist, crystalline ls., gneiss	Granite, gneiss, charnockite, schist	Granite, schist, gneiss

stone commonly becomes pink or brown. Thickness is difficult to determine, as it seems that there is not one but several limestone zones within the metamorphic complex. The thickest zone has been estimated as from 4000 to 6000 feet; the relation of the limestone to the other metamorphic rocks has not been determined.

The plutonic rocks of the Precambrian basement are younger than the metamorphics. The granites consist of two distinct types, a gray biotite granite and a younger pink hornblendic biotite granite. The gray granite commonly contains inclusions of metamorphic rocks, primarily gneisses, granulites, and marble. Aplite dikes also are common in the gray granite. The pink granite is less coarsely crystalline than the gray and from data available at scant exposures it seems that it occurs as a thin sheet, usually above the gray granite. Veins of pink aplite and pegmatite cut the pink granite.

Elsewhere in East Antarctica the basement complex is less diversified. In Wilkes Land along King George V and Adelie Coasts the basement contains igneous and metamorphic rocks similar to those of Victoria Land. Westward, however, through Knox Coast to Enderby Land, the basement complex is characterized by the presence of charnockite rocks (hypersthene granites and their relatives). Alkalic granites, gneisses, and metamorphic rocks similar to those of Victoria Land are present.

In the area of Princess Martha Coast the British-Norwegian-Swedish Expedition mapped extensive areas of basement rocks consisting of hornblende-biotite gneiss, garnetiferous gneiss, and amphibolite. Minor amounts of migmatite, granitic gneiss, and pegmatite along with chlorite schist and quartzite are present. Aerial photos taken by the German expedition in 1939 indicate that the same type extends eastward in the mountain masses behind Princess Astrid Coast.

In Victoria Land and extending southeastward in

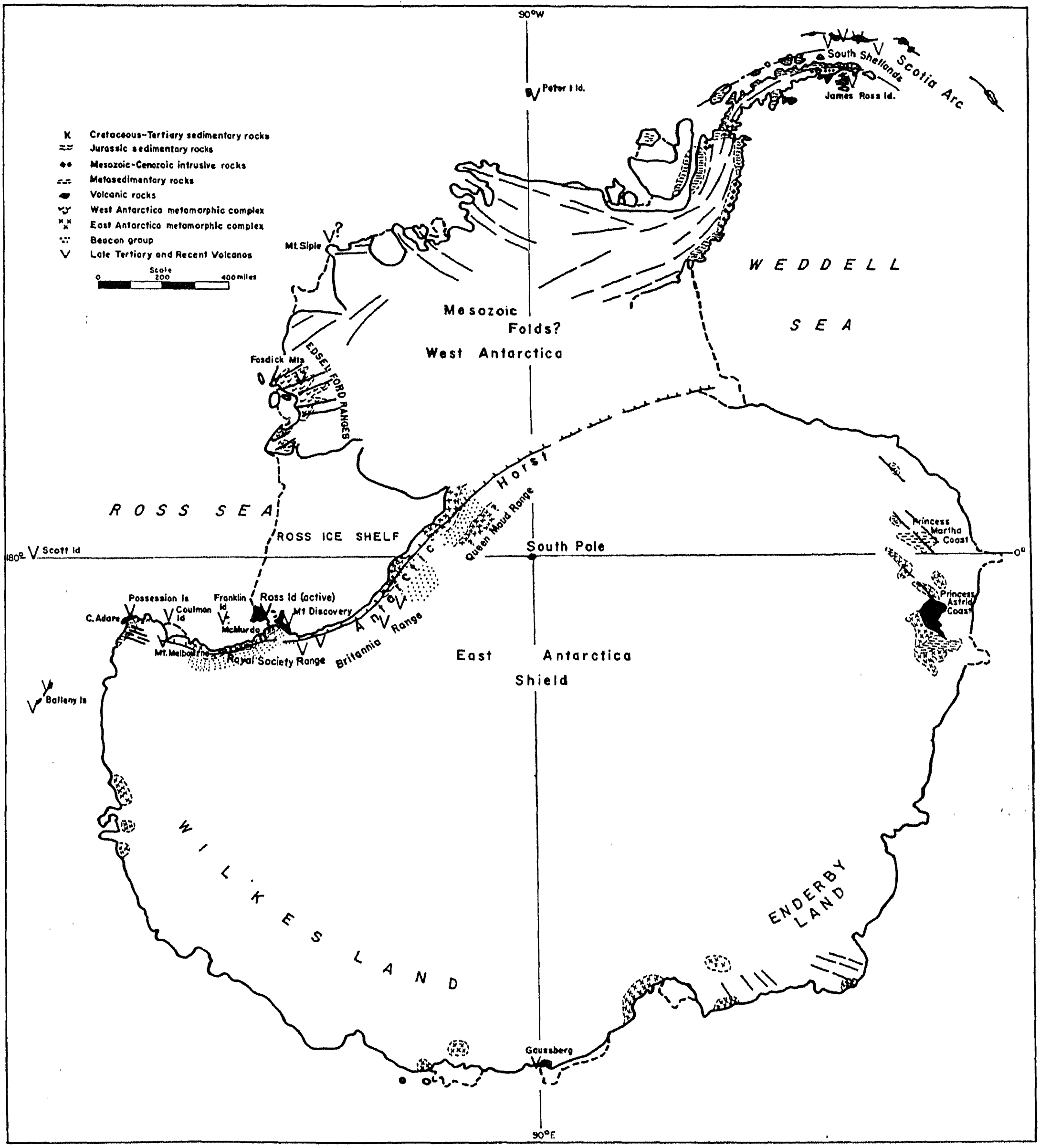

FIG. 2 – Antarctic geology

the Queen Maud Ranges a thick sequence of sedimentary rocks overlies the basement complex. At the base is a limestone of Cambrian age. The limestone is massive but unmetamorphosed and is in part dolomitized and silicified. Fragments of this limestone have been recovered only in the area along the Beardmore Glacier and very little is known concerning its occurrence and stratigraphic relationship except that definitive Cambrian fossils are contained in it.

The greatest thickness of sedimentary rock in the area of the Ross Sea is that of the Beacon group. This sequence consists of flat-lying, fine-grained quartz sandstones and arkoses, with thin conglomerates, shale, lignitic coal, and thin limestones. Ripple marks, crossbedding, and sun cracks are common, indicating a continental or shallow-water environment during the deposition of the sediments. The age of the Beacon group extends from late Paleozoic through early Mesozoic. Near the base fossil fish of possible Devonian age have been found and lower Mesozoic plant remains have been recovered in the upper part.

The Beacon group as well as part of the base-

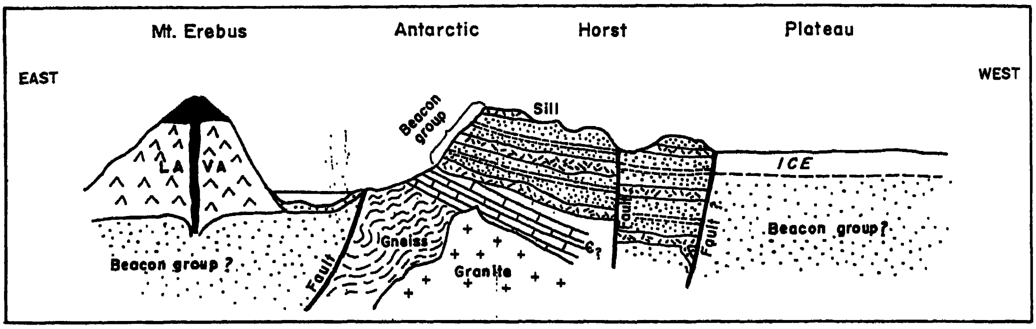

FIG. 3 – Diagrammatic geologic profile of McMurdo Sound, East Antarctica [after *Taylor*, 1930]

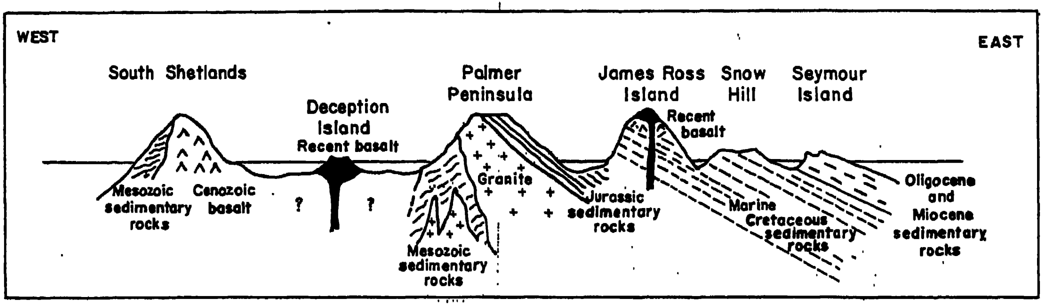
WEST
EAST
South Shetlands
Deception Island
Recent basalt
Palmer Peninsula
James Ross Island
Snow Hill
Seymour Island
Recent basalt
Mesozoic sedimentary rocks
Cenozoic basalt
?
?
Granite
Mesozoic sedimentary rocks
Jurassic sedimentary rocks
Marine Cretaceous sedimentary rocks
Oligocene and Miocene sedimentary rocks

FIG. 4 – Diagrammatic geologic profile of Palmer Peninsula, West Antarctica [after *Taylor*, 1930]

ment complex are intruded by dikes and enormous sills of diabase. Sills are several hundred to 2000 feet thick and have an aggregate thickness of over 4000 feet.

In the vicinity of Cape Adare there is a belt of folded rocks, the Robertson Bay group. This sequence consists of slates and graywackes only slightly metamorphosed. Numerous quartz veins cut the rocks. The age of these rocks is not known although they have been tentatively assigned to the early Paleozoic.

The only other sedimentary rocks in the East Antarctic shield are in the area of Princess Martha Coast where slates and graywackes are present. These rocks, only slightly deformed, have undergone slight to moderate metamorphism. Thickness is between 2000 and 6000 feet. These sediments have been invaded by numerous diabase sills, some up to 1800 feet thick.

The geology of West Antarctica is a reflection of the Andean type rocks of South America (Fig. 2). The Andean folding can be traced from Cape Horn through South Georgia and the South Orkneys to the Palmer Peninsula. This connection, the Scotia Arc, consists of a volcanic belt on the western flank of the folds, a central folded belt with a core of plutonics, and an eastern flank of Mesozoic and Cenozoic sedimentary rocks.

The basement rocks in West Antarctica are gabbros and granodiorites of the Andean type (Fig. 4). Precambrian metamorphic rocks are insignificant in extent and the overlying sediments rest on the planed surface of the plutonic rocks.

The oldest sedimentary rocks are along the Scotia Arc in the South Orkneys. Here a sequence or shales, graywackes, and phyllites contain graptolites indicating an Ordovician Age. Dredging, however, near the South Orkneys has recovered limestone with Cambrian fossils, indicating that older sediments form part of the Arc.

In the Palmer Peninsula the oldest sedimentary rocks are of Mesozoic age. They are a series of slates, sandstones, and conglomerates containing a rich flora of Jurassic age. These occur along the eastern side of the Palmer Penisula as far south as the Lassiter Shelf Ice. A similar Jurassic sequence but with limestones occurs along the east side of Alexander I Island in the southwestern part of the Palmer Peninsula.

The Jurassic sedimentary rocks are folded and invaded by volcanics consisting of andesites, dacites, and rhyolites with tuffs and quartz porphyries. On the west side of the peninsula the Mesozoic sedimentary rocks have undergone slight to moderate metamorphism. On the east side of the arc metamorphism has not been very extensive.

The youngest Mesozoic rocks are the Snow Hill group, which occurs on the islands at the northeastern end of the Palmer Peninsula. The sequence consists of a basal conglomerate resting on tuffs of Mesozoic age. Overlying the conglomerate is a sandstone which is locally glauconitic, noncalcareous, and shaly. A rich fossil assemblage of Cretaceous plants and invertebrates occurs in the sandstone. Unconformably overlying the Snow Hill group is the Seymour Island group, consisting of 500 feet of conglomerates and sandstones. Tuffaceous beds occur near the base. These are mainly continental deposits and contain a rich Eocene and Oligocene flora. In the upper part of the Seymour Island group there is a marine deposit of calcareous sands which carries a rich Oligocene and Miocene fauna.

The youngest sedimentary rocks of significant extent are the so-called 'Pecten' beds on Cockburn Island off the northeastern part of the Palmer Peninsula. Here a basalt tuff is overlain by a conglomerate of basalt debris cemented by ash. It is rich in invertebrate fossils of either late Pliocene or early Pleistocene age.

Little is known of the geology of Marie Byrd Land. Folded, partly metamorphosed but unfossiliferous sediments (quartzites and slates) about 15,000 feet in thickness have been mapped in the Edsel Ford Ranges and in the Rockfeller Mountains. Plutonic masses that have invaded the folded sediments include granite, granodiorite, and quartz monzonite. The relation of these rocks to those in the remainder of West Antarctica is questionable. The trend at present is to match the rocks of the Edsel Ford Range with those of the Andean-type rocks of the Palmer Peninsula. Topographic trends in Marie Byrd Land lend support to this hypothesis.

Pleistocene and Recent volcanism has been extensive in many places along the coast of Antarctica (Fig. 2). The South Shetlands, the western arc of islands lying off Palmer Peninsula, contain several dormant volcanoes. Peter I Island, 600 miles west of the Palmer Peninsula, also is volcanic. In the Ross Sea area Scott Island, the Balleny Islands, Ross Island, and several smaller islands are volcanic. On the mainland volcanoes are in the Edsel Ford Range, at Gaussberg in Wilkes Land, and at several points in Victoria Land. In Marie Byrd Land Mt. Siple may possibly be volcanic in origin. The lavas vary considerably in composition. At Mt. Erebus, on Ross Island, the only volcano now active, the older lavas are trachytes and basalts. The bulk of the modern cone is of kenyte-type lava, characterized by the presence of large crystals of anorthoclase feldspar. Elsewhere lavas are leucite basalt, olivine basalt, and andesite.

Structurally the two divisions of Antarctica can be related to adjacent continental masses. West Antarctica is tied to the Andean land mass of South America. East Antarctica, a part of the Gondwana land mass, is probably related tectonically to Australia, South Africa, and Brazil.

Within the Antarctic continent there are two distinct types of structure (Fig. 2). East Antarctica, with its shield development, is relatively simple. It consists of undisturbed, horizontally bedded sedimentary rocks lying on a basement complex. Along the Ross Sea the shield is intersected by a series of block faults that give rise to a high horst area. Evidence from glacial erratics indicates that the block faulting may continue well into the plateau, with an interior horst being elevated behind the Queen Maud Range to bring the basement rocks to the surface. Inland from the horsts the plateau surface slopes gently and the overlying sediments have probably been eroded, exposing the basement rocks over much of the shield.

In West Antarctica the folds in the Scotia Arc and Palmer Peninsula are extensions of those in the Andes. In this area is a single major flexure flanked on the west and north by volcanic ridges and on the east and south by gently dipping sediments. At the base of the Palmer Peninsula the folds become multiple and are believed to fan out in Marie Byrd Land. A graben connecting the Weddell and Ross Seas has been postulated but its existence is as yet unproved.

The mineral resources of the Antarctic have been stressed in the press to the point that the layman looks upon it as an area of considerable wealth. However, no mineral resource has been proved as yet.

Coal has been found in the Beacon group but it is of varying quality, ranging from lignite to anthracite. It has been observed at four points in an area corresponding in size to the Appalachian Mountains. From these four observations rather large reserves have been estimated. Considering the complexities and size of the diabase intrusions and their effect on coal beds, as well as the vagaries of the coal seams themselves, it seems that even conservative estimates need to be restrained. Although no finds of economic value have been made, copper, silver, and related sulfide ore deposits of the Andean type are possible in the Palmer Peninsula area. The metamorphic and igneous rocks of the basement complex of the East Antarctic shield contain rock types that are indicative of the possibility of nickel, iron, manganese, tin, lead, and possibly uranium. It is conceivable that oil may be

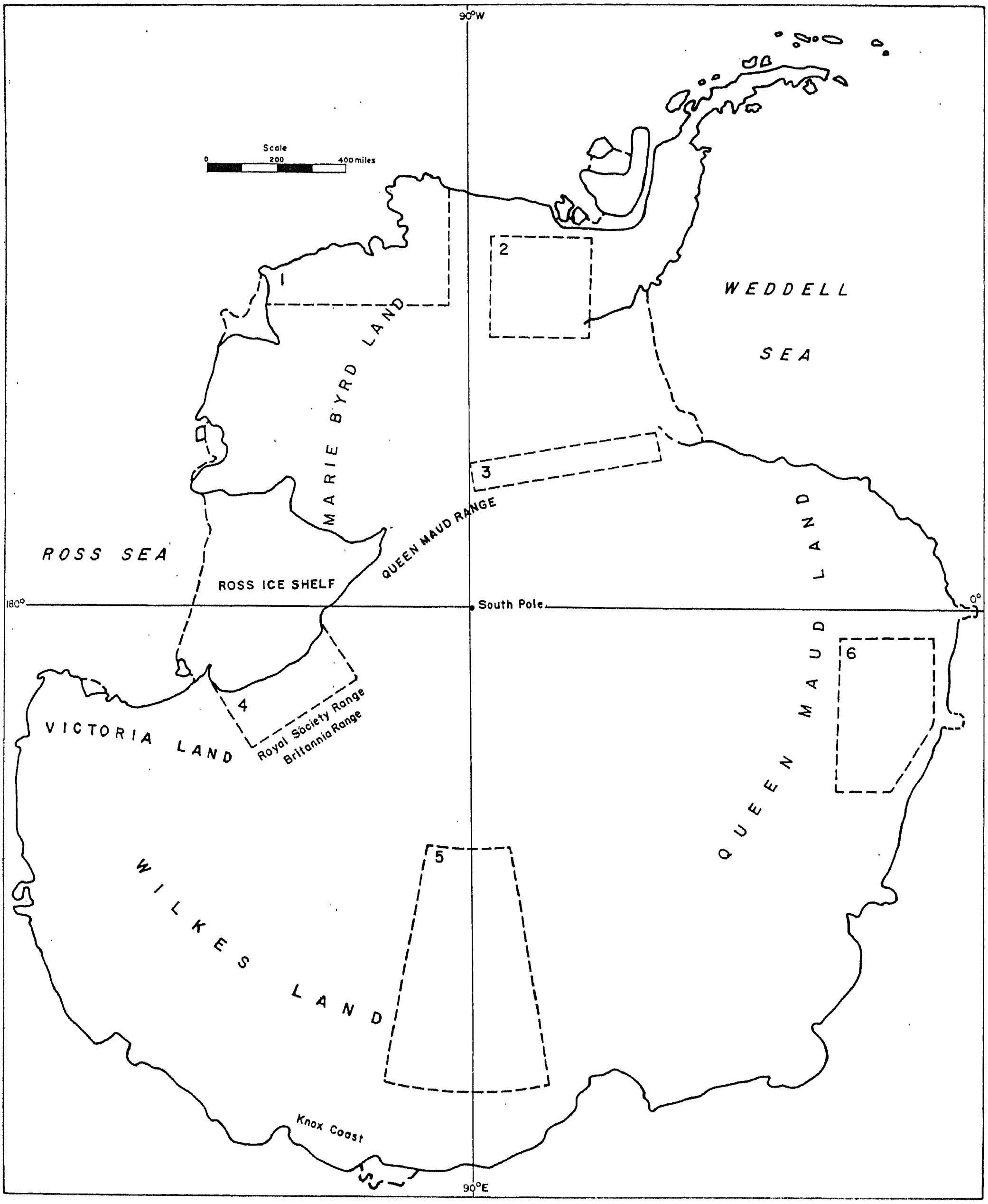

FIG. 5 – Antarctic areas of interest in the near future for geological information

present in the undisturbed sedimentary rocks, but no direct evidence on that point is yet available.

Problems in Antarctic geology are numerous. In addition to just plain covering the ground the following areas seem to offer the best returns upon investigation (Fig. 5): (1) Geology of the interior of Marie Byrd Land. This should give information on the trend of the Antarctic Andes. (2) Investigations at the base of the Palmer Peninsula to supplement data obtained in Marie Byrd Land. (3) Investigations eastward along the front of the Queen Maud Range. These would give data on the supposed graben in the area, as well as closing the last link around the shield area. Unfortunately the British Transpolar Expedition plans to follow the plateau in 1956 and 1957 and will miss this interesting area. (4) Detailed surveys in the Royal Society and Britannia Ranges of Victoria Land. These would yield data on the coal reserves so often cited, as well as establishing the stratigraphy and structure of the Beacon group. (5) Investigations inland in the zone 80°–100°E to determine if high mountainous areas exist there as indicated by meteorological observations. (6) Extension of the work of the British Norwegian-Swedish Expedition into the area of Princess Astrid Coast. Aerial photographs obtained by the German Expedition in 1939 indicated that this area presents geologic features of a nature different from that of much of the Antarctic Shield.

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On the Petrology of Antarctica

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Abstract—Since 1895 over 100 papers have been published relating to the chemistry, mineralogy, petrography, and petrology of Antarctic rocks. Listed are 174 mineral species, subspecies, and varieties, as well as those of questionable occurrence, that have been reported from Antarctica. A number of these have been determined only microscopically, and in the case of gold its presence has been determined only by chemical analysis. Two hundred and thirty-four chemical analyses are tabulated. The chemical analyses are of 15 minerals and 181 igneous, 4 sedimentary, and 34 metamorphic rocks. The rocks are described on the basis of areal distribution.

Introduction—The first paper to be printed on Antarctic rocks was that of *Petersen* [1895, pp. 275–278], which contains a description of a basalt from Mount Christen Christensen (Christensen-Vulkan), Robertson Island, lying southward of Nordenskjöld Coast.

A total of 174 mineral species, subspecies, and varieties, as well as those of questionable occurrence are listed in the literature (Table 1). Minerals of potential commercial value include atacamite, azurite, bornite, cassiterite, chalcopyrite, chromite, galena, gold, hematite, magnetite, malachite, molybdenite, sphalerite, and stibnite. Uranium-bearing minerals have not been recorded. However, inasmuch as Antarctica is a shield area it is suggested that eventually ore deposits will be discovered.

Two hundred and thirty-four chemical analyses of Antarctic minerals and rocks are recorded (Tables 2–5), including 15 minerals and 181 igneous, 4 sedimentary, and 34 metamorphic rocks. The British have contributed 50 pct of the analyses, 41 pct represent contributions by French, German, Norwegian, and Swedish expeditions, and the Americans list less than nine per cent of the total. *Smith* [1954, p. 91] in his concluding remarks on the volcanic rocks of the Ross Archipelago states:

> "When one seeks to find whether the volcanic rocks are members of one or more differentiation series one finds that the chemical analyses available are too few to warrant very definite deductions from differentiation diagrams and other recognized methods of plotting analyses."

The areal distribution of Antarctic rocks is treated under the following headings: (1) Luitpold Coast—Palmer Peninsula and outlying islands, (2) Marie Byrd Land—Victoria Land and outlying islands, (3) George V and Adelie Coasts, and (4) Queen Mary, Wilhelm II, Ingrid Christensen, Mac-Robertson, and Kemp Coasts, and Enderby Land.

In most instances Antarctic toponymy follows the decisions rendered by the U. S. Board on Geographical Names, in *The Geographical Names of Antarctica* (1947, 1949, and 1951). In a few instances *The Antarctic Pilot* (1948) and the *Gazetteer of the Falkland Islands Dependencies* (1955) were relied upon for information relating to the nomenclature of Antarctica.

Rocks of Luitpold Coast—Only one paper [*Capurro*, 1955, pp. 129–131] has been published on rocks collected on Luitpold Coast. The specimens are recorded as being granophyric granite, impure crystalline limestone, and spillite, and were obtained at Bertrab Nunatak.

Rocks of Palmer Peninsula and outlying islands—Many collections of rocks have been made on Palmer Peninsula and its outlying islands. Contributing to our knowledge of this part of the Antarctic are the works of *Adie* [1954, 1955], *Baeckström* [1915], *Barth* and *Holmsen* [1939], *Barth* [1940], *Barth* and *Kvalheim* [1944], *Bodman* [1916], *Broch* [1927], *Geikie* [1898], *Gourdon* [1905, 1906, 1907, 1908, 1910, 1914abc, 1917], *Holtedahl* [1929], *Knowles* [1945], *Nordenskjöld* [1905], *Pelikan* [1909], *Petersen* [1895], *Prior* [1898], *Stewart* [1934ae, 1937, 1945, 1947], *Thomas* [1921], *Tilley* [1930], *Tyrrell* [1921, 1945], and *Wordie* [1921]. Ninety-five chemical analyses of igenous rocks and five of metamorphic rocks have been recorded (Table 2).

Adie [1954] reports that the Basement Complex, assigned to the Archean, and composed of seven kinds of gneisses, one amphibolite, and three schists, has been found to be restricted to the Fallieres Coast of southwestern Palmer Peninsula. He records descriptions of granites which are younger than the basement complex, yet older than the Jurassic andesitic lavas and agglomerates.

TABLE 1 – *Minerals reported from Antarctica*

Acmite
Actinolite
Adularia
Aegirine-augite
Allanite
Almandite
Analbite?
Analcite
Anatase
Andalusite
Andesine
Andradite
Anomite
Anorthite
Anorthoclase
Anthophyllite
Antigorite
Apatite
Aphrosiderite
Apophyllite
Arfvedsonite
Arsenopyrite
Atacamite
Augite
Azurite
Barkevikite
Basaltic hornblende
Beryl
Biotite
Bowlingite?
Bornite
Bronzite
Brookite
Brucite
Brushite?
Bytownite
Calcite
Cancrinite
Cassiterite
Ceylonite
Chalcopyrite
Chlor-apatite
Chloritoid
Chondrodite
Christensenite
Chrome diopside
Chromite
Chryoslite
Chrysotile
Clinochlore
Clinoenstatite
Clinohumite?
Clinohypersthene
Cordierite
Corundum
Cossyrite
Cristobalite?
Cummingtonite
Damourite
Delessite
Diallage
Diopside
Dolomite
Dumortierite
Edenite
Enstatite
Enstatite-augite
Fassaite?
Fayalite
Ferrimolybdite
Fluorite
Forsterite
Galena
Glauconite
Glaucophane
Gold
Graphite
Grossularite
Gypsum
Haüyne
Hedenbergite
Hematite
Hercynite
Heulandite
Hornblende
Hyalosiderite
Hypersthene
Iddingsite
Ilmenite
Kaersutite?
Kaolinite
Katophorite?
Kornerupine?
Kyanite
Labradorite
Laumontite
Lawsonite
Lepidolite
Lepidomelane
Leucite
Leucoxene
Limonite
Magnetite
Malachite
Malacolite
Meionite
Mesolite
Microcline
Microperthite
Mirabilite
Mizzonite
Molybdenite
Muscovite
Natrolite
Nephelite
Newberyite?
Nosean
Oligoclase
Olivine
Orthoclase
Paragonite?
Pargasite
Penninite
Phlogopite
Picotite
Piedmontite
Pigeonite
Pinite
Pistacite
Prehnite
Prochlorite
Pyrite
Pyrrhotite
Quartz
Riebeckite
Rutile
Salite
Sanidine
Sapphire
Scapolite
Schreibersite
Scolecite
Sericite
Serpentine
Siderite
Sillimanite
Sodalite
Soda-orthoclase
Spessartite?
Sphalerite
Sphene
Spinel
Stercorite
Stibnite
Stilbite
Talc
Tetrahedrite
Thomsonite
Titaniferous aegirine-augite
Titaniferous augite
Titanomagnetite
Topaz
Tourmaline
Tremolite
Tridymite
Troilite
Vermiculite?
Vesuvianite
Woehlerite
Wollastonite
Xenotime
Zircon
Zoisite

These rocks have been observed at a number of localities along the Fallieres Coast. Early Paleozoic volcanics of andesitic composition were collected from Alexander I Island, off southwest coast of Palmer Peninsula, and Pourquois Pas Island, off Bowman Coast.

Adie [1955] ably discusses the Andean granite-gabbro suite of Palmer Peninsula, and describes granites, including those from Cape Roquemaurel and Mount Reece, Louis Philippe Peninsula, Gulliver Nunatak, Oscar II Coast, and Marguerite Bay area, Fallieres Coast; granodiorites from the Mount Bransfield area, Louis Philippe Peninsula; quartz diorites from Hope Bay, Louis Philippe Peninsula, Marguerite Bay area, Fallieres Coast, and east coast of Palmer Peninsula from Three Slice Nunatak southward to Bowman Peninsula; hornblende-biotite diorites from Tabarin Peninsula, Louis Philippe Peninsula, and Marguerite Bay area, Fallieres Coast; gabbros from Hope Bay area, Louis Philippe Peninsula, Marguerite Bay area, Fallieres Coast, and Cape Bryant, Richard Black Coast. Hornblendites are briefly mentioned.

Baeckström [1915] describes some basalts from Cockburn, James Ross, and Snow Hill Islands, southeast of Louis Philippe Peninsula, Paulet Island, east of Louis Philippe Peninsula, and Robertson Island, southward of Nordenskjöld Coast.

Barth and *Holmsen* [1939] have published petrographical data for recent lavas of Deception Island, South Shetland Islands, which are discussed under the headings of neutral and acid lavas. Andesine basalt, pillow lava (bandaitic composition), and tridymite santorinite are described. From a small islet in the vicinity of Victor Hugo Island, off Graham Coast, were collected eucrites with bands of anorthositic composition. Included are petrographical descriptions of rock samples from the Port Lockroy area, Wiencke Island, Palmer Archipelago, and the outer parts of Flanders Bay, which are quartz dioritic. Adamellite and diabase from Port Lockroy are also referred to. Dolerite from Admiralty Bay, King George Island, South Shetland Islands, is described. Analyses of igneous breccias from Joubin Islets, Palmer Archipelago, and Peltier Sound are listed. Tuffs from various islands of the archipelago are described. Reference is made to the green schists of Clarence Island,

TABLE 2 – *Chemical analyses of rocks from Palmer Peninsula and outlying islands*

Item	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
SiO_2	77.69	75.30	75.00	74.79	73.44	73.25	73.12	73.01	72.53	71.88	71.10	69.01	69.00	68.28	67.71	67.59	66.39	66.05	64.67	64.33	63.5	63.42	63.01	62.97	62.31
TiO_2	0.25	n.d.	...	0.29	0.22	tr.	0.39	...	0.18	0.60	0.46	0.58	0.22	0.70	1.00	0.28	0.33	0.35	0.51	n.d.	0.7	0.92	0.56	0.10	0.72
Al_2O_3	11.55	11.50	13.79	13.29	14.33	12.60	13.67	14.07	14.55	14.88	14.50	14.21	16.93	15.95	14.65	14.65	17.62	15.36	15.39	16.71	17.2	18.88	13.61	14.75	17.28
Fe_2O_3	1.40	...	...	nil	0.52	0.34	0.85	...	...	0.40	0.31	2.23	0.63	2.00	1.59	...	1.01	...	...	...	2.7	1.43	...	2.98	2.65
FeO	0.44	3.44	1.05	2.06	1.18	2.65	1.51	1.94	1.59	3.08	3.10	2.89	1.65	1.82	3.29	5.55	2.21	4.37	5.26	4.52	1.9	3.54	5.50	3.31	1.67
MnO	...	...	...	tr.	0.02	...	...	...	0.80	...	...	...	0.04	...	...	...	...	...	...	...	...	...	0.85	0.17	0.05
MgO	0.02	0.18	0.20	0.04	0.21	0.51	0.54	0.44	tr.	0.07	1.17	0.62	0.60	0.09	0.85	1.34	1.32	4.15	1.41	1.60	1.1	1.22	2.42	2.12	1.41
CaO	4.79	1.32	0.80	1.93	2.13	tr.	1.37	1.77	0.99	2.97	2.59	2.11	3.68	1.78	2.34	3.46	3.79	2.97	3.89	4.47	3.0	4.10	4.29	5.51	2.42
Na_2O	1.13	4.60	4.10	4.06	3.09	5.37	2.66	2.56	2.91	3.12	3.25	6.30	3.16	7.03	6.09	3.34	4.49	3.60	1.98	4.36	5.5	5.34	2.15	3.78	6.72
K_2O	2.15	2.85	3.62	2.32	3.87	3.95	5.23	5.46	5.85	1.44	4.02	2.07	3.29	1.75	1.99	3.64	2.13	2.47	4.61	2.91	3.2	0.97	5.56	1.21	3.58
H_2O+	{1.05	{0.17	{0.24	0.88	0.52	{0.75	{0.67	{0.58	{0.76	{1.27	{0.25	{0.09	0.76	{0.24	{0.16	{0.91	6.39	{0.67	{0.29	{0.34	{1.7	{0.39	{0.57	{2.15	0.11
H_2O-				0.09	0.11								0.11				...								0.30
P_2O_5	0.01	...	...	tr.	0.29	...	...	...	...	...	0.03	0.12	0.11	0.07	0.16	...	...	...	...	...	n.d.	...	...	0.07	0.29
CO_2	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	0.00
ZrO_2	...	...	...	nil	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
Cl	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	0.34
F	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
S	...	...	...	0.29	...	...	...	...	...	0.21	...	...	...	...	...	...	...	...	...	...	...	...	...	...	0.03
SO_3	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
BaO	...	...	...	tr.	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	0.06
Cr_2O_3	...	...	...	nil	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
(Ni,Co)O	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
Li_2O	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	tr.	...
	100.48	99.36	98.80	99.92	99.93	99.42	100.01	99.43	100.16	99.74	100.78	100.23	100.18	99.71	99.83	100.74	99.68	99.99	98.01	99.14	100.5	100.21	98.55	99.12	99.94

1. Quartz porphyrite (boulder), Port Lockroy, Wiencke Island, Palmer Archipelago [*Barth* and *Holmsen*, 1939, p. 27]; analyst: Brynjolf Bruun.

2. Granite (erratic), Seymour Island, southeast of Louis Philippe Peninsula [*Bodman*, 1916, p. 9]; analyst: G. Bodman.

3. Microcline granite (erratic), Seymour Island, southeast of Louis Philippe Peninsula [*Bodman*, 1916, p. 5]; analyst: G. Bodman.

4. Prehnitized rock fragment in breccia, Joubin Islets, Palmer Archipelago [*Barth* and *Holmsen*, 1939, p. 29]; analyst: Brynjolf Bruun.

5. Biotite granite, Cape Roquemaurel, Louis Philippe Peninsula [*Adie*, 1955, p. 24]; analyst: R. J. Adie.

6. Soda pyroxene-amphibole microgranite (erratic), Booth Island, Dannebrog Islands group, off Graham Coast [*Gourdon*, 1908, p. 200]; analyst: Pisani.

7. Adamellite, Port Lockroy, Wiencke Island, Palmer Archipelago [*Barth* and *Holmsen*, 1939, p. 22]; analyst: Brynjolf Bruun.

8. Granite (erratic), Cockburn Island, southeast of Louis Philippe Peninsula [*Bodman*, 1916, p. 14]; analyst: G. Bodman.

9. Granite (erratic), Red Island, Gustav Channel, off Louis Philippe Peninsula [*Bodman*, 1916, p. 12]; analyst: G. Bodman.

10. Igneous breccia, Joubin Islets, Palmer Archipelago [*Barth* and *Holmsen*, 1939, p. 32]; analyst: Brynjolf Bruun.

11. Amphibole granite, Booth Island, Dannebrog Islands group, off Graham Coast [*Gourdon*, 1908, p. 144]; analyst: Pisani.

12. Trachyandesite, Deception Island, South Shetland Islands [*Gourdon*, 1917, p. 7]; analyst, Boiteau.

13. Biotite granite, Mount Reece, Louis Philippe Peninsula [*Adie*, 1955, p. 24]; analyst: R. J. Adie.

14. Tridymite santorinite, Deception Island, South Shetland Islands [*Barth* and *Holmsen*, 1939. p. 14]; analyst: Brynjolf Bruun.

15. Trachyandesite, Deception Island, South Shetland Islands [*Gourdon*, 1917, p. 7]; analyst: Boiteau.

16. Tonalite (erratic), summit of Borchgrevink Nunatak, Oscar II Coast [*Bodman*, 1916, p. 21]; analyst: G. Bodman.

17. Quartz diorite (dredged block), 70°S, 81°W (Paris), Bellingshausen Sea [*Washington*, 1917 p. 267]; analyst: Lassieur.

18. Tuff, depot, Hope Bay, Louis Philippe Peninsula [*Bodman*, 1916, p. 67]; analyst: G. Bodman.

19. Quartz-mica diorite, Hope Bay, Louis Philippe Peninsula [*Bodman*, 1916, p. 25]; analyst: G. Bodman.

20. Quartz-mica diorite (erratic), Hope Bay, Louis Philippe Peninsula [*Bodman*, 1916, p. 25]; analyst: G. Bodman.

21. Hornblende-mica trachyandesite, Jeanne Hill, Booth Island, Dannebrog Islands group, off Graham Coast [*Gourdon*, 1908, p. 166]; analyst: Pisani.

22. Igneous breccia, Peltier Channel, Palmer Archipelago [*Barth* and *Holmsen*, 1939, p. 32]; analyst: Brynjolf Bruun.

23. Quartz-mica diorite (erratic), Hope Bay, Louis Philippe Peninsula [*Bodman*, 1916, p. 25]; analyst: G. Bodman.

24. Malchit, Banck Island, Palmer Archipelago [*Pelikan*, 1909, p. 45]; analyst: Zdarek.

25. Trachyandesite, Peter I Island, northeast of Thurston Peninsula [*Broch*, 1927, p. 38]; analyst: Emil Klüver.

TABLE 2 (continued) – *Chemical analyses of rocks from Palmer Peninsula and outlying islands*

Item	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50
SiO_2	61.79	61.45	61.03	60.80	60.62	60.36	60.19	59.94	59.85	59.67	58.97	58.85	58.35	57.98	57.46	57.30	57.28	56.89	56.30	56.10	55.33	55.27	55.15	54.61	54.36
TiO_2	1.22	0.80	0.65	0.65	1.54	0.92	1.15	0.58	0.84	0.72	1.64	0.82	0.80	0.84	1.15	0.56	0.84	1.79	0.06	0.76	0.14	tr.	1.57	1.66	0.32
Al_2O_3	16.20	16.58	15.87	16.08	16.22	17.01	16.12	18.12	16.90	16.99	16.75	17.48	16.91	18.18	15.95	17.97	16.70	16.07	15.91	19.81	14.72	16.59	17.56	19.10	18.49
Fe_2O_3	2.64	2.83	2.26	2.35	1.76	1.43	3.97	3.19	1.92	2.77	...	2.98	1.79	2.00	1.96	2.17	4.23	1.81	3.15	2.07	6.11	6.03	4.12	3.65	...
FeO	3.62	2.87	3.22	3.00	5.67	3.93	3.07	2.63	5.22	4.04	7.80	3.27	5.71	4.59	5.82	3.79	4.15	7.08	6.38	5.15	5.34	5.81	4.46	3.73	6.93
MnO	...	0.10	0.08	0.09	...	0.07	...	0.08	...	0.10	...	...	...	...	...	...	...	0.08	tr.	...	0.18	tr.	...	...	...
MgO	1.96	2.37	2.94	3.50	1.62	2.64	2.14	2.00	3.12	2.55	2.06	2.53	4.34	3.67	3.77	2.57	3.70	2.79	3.64	3.44	3.91	2.80	3.37	3.06	4.10
CaO	4.68	5.70	5.71	5.31	4.18	4.14	4.35	6.60	6.63	5.89	5.67	6.24	6.88	7.28	7.26	6.72	7.66	5.89	8.10	7.20	7.56	6.65	6.94	6.51	6.45
Na_2O	3.69	3.36	3.56	3.97	6.25	3.47	5.22	2.88	3.45	3.48	4.38	3.56	2.99	1.26	2.28	3.25	3.21	5.89	3.41	3.55	3.23	4.23	3.18	4.34	4.39
K_2O	2.98	2.78	2.52	2.09	1.20	2.95	1.97	2.27	1.28	2.61	1.71	1.97	1.33	4.07	2.82	0.96	1.41	0.94	1.17	1.08	1.26	0.64	1.31	1.27	2.21
H_2O+	0.78	0.67	1.57	1.55	0.56	2.34	1.38	0.81	0.87	0.49	0.91	2.03	0.35	0.45	...	4.26	0.78	0.56	1.74	0.75	1.57	1.59	1.88	2.63	2.16
H_2O-	...	0.11	0.21	0.12		0.11		0.10		0.16		...	...	...	1.60		0.02	0.08							
P_2O_5	0.28	0.36	0.19	0.33	0.24	0.41	0.30	0.34	0.06	0.35	0.38	0.12	...	0.12	0.19	0.20	0.13	0.21	0.16	tr.	0.53	0.52	0.21	0.32	...
CO_2	...	...	...	0.09	...	0.06	...	0.29	...	tr.	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
ZrO_2	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
Cl	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
F	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
S	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	0.06	...	...	...	...	...	...	...
SO_3	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
BaO	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
Cr_2O_3	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
(Ni,Co)O	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
Li_2O	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	tr.	...	...	...	...
	99.84	99.98	99.81	99.93	99.86	99.84	99.86	99.83	100.14	99.82	100.65	99.85	99.45	100.44	99.76	99.75	100.11	100.08	100.02	99.91	99.88	100.13	99.75	100.88	99.41

26. Diorite (dredged block), 70°S, 81°W (Paris), Bellingshausen Sea [*Washington*, 1917, p. 401]; analyst: Boiteau.

27. Quartz diorite, Brown Bluff, Tabarian Peninsula, Louis Philippe Peninsula [*Adie*, 1955, p. 24]; analyst: R. J. Adie.

28. Quartz diorite, Millerand Island, Marguerite Bay, off Fallieres Coast [*Adie*, 1955, p. 24]; analyst: R. J. Adie.

29. Quartz diorite, Millerand Island, Marguerite Bay, off Fallieres Coast [*Adie*, 1955, p. 24]; analyst: R. J. Adie.

30. Andesite, Deception Island, South Shetland Islands [*Gourdon*, 1917, p. 7]; analyst: Lassieur.

31. Quartz-biotite diorite, Gulliver Nunatak, Oscar II Coast [*Adie*, 1955, p. 24]; analyst: R. J. Adie.

32. Acid andesite, Jenny Island, off southeast coast of Adelaide Island [*Gourdon*, 1917, p. 9]; analyst: Boiteau.

33. Quartz-biotite diorite, Mineral Hill, Louis Philippe Peninsula [*Adie*, 1955, p. 24]; analyst: R. J. Adie.

34. Mica-quartz diorite, Booth Island, Dannebrog Islands group, off Graham Coast [*Gourdon*, 1908, p. 151]; analyst: Pisani.

35. Hypersthene-bearing quartz diorite, Mount Bransfield area, Louis Philippe Peninsula [*Adie*, 1955, p. 24]; analyst: R. J. Adie.

36. Quartz diorite, Cape Hamilton, James Ross Island, southeast of Louis Philippe Peninsula [*Bodman*, 1916, p. 34]; analyst: G. Bodman.

37. Quartz diorite, Berthelot Islets, off Graham Coast [*Washington*, 1917, p. 403]; analyst: Boiteau.

38. Quartz-biotite diorite, Hovgaard Island, Dannebrog Islands group, off Graham Coast [*Washington*, 1917, p. 419]; analyst: Lassieur.

39. Quartz-mica diorite, Vedel Island, Vedel Islets, Dannebrog Islands group, off Graham Coast [*Washington*, 1917, p. 405]; analyst: Lassieur.

40. Quartz diorite, Hovgaard Island, Dannebrog Islands group, off Graham Coast [*Washington*, 1917, p. 369]; analyst: Boiteau.

41. Hypsersthene andesite, Admiralty Bay, King George Island, South Shetland Islands [*Gourdon*, 1917, p. 7]; analysts: Lassieur and Boiteau.

42. Quartz diorite, Port Lockroy, Wiencke Island, Palmer Archipelago [*Barth* and *Holmsen*, 1939, p. 21]; analyst: Brynjolf Bruun.

43. Pillow lava (bandaitic composition), Deception Island, South Shetland Islands [*Barth* and *Holmsen*, 1939, p. 11); analyst: Brynjolf Bruun.

44. Quartz diorite, Two Hummock Island, Palmer Archipelago [*Pelikan*, 1909, p. 13]; analyst: Zdarek.

45. Hornblende labradorite, Port Lockroy, Wiencke Island, Palmer Archipelago [*Gourdon*, 1908, p. 183]; analyst: Pisani.

46. Quartz-augite diorite, Moreno Island, Palmer Archipelago [*Pelikan*, 1909, p. 7]; analyst: Zdarek.

47. Quartz diorite, Cape Anna, Danco Coast [*Pelikan*, 1909, p. 21]; analyst: Zdarek.

48. Andesite, Jenny Island, off southeast coast of Adelaide Island [*Gourdon*, 1917, p. 9]; analyst: Boiteau.

49. Hornblende andesite (beach erratic), Roosen Channel, near Port Lockroy, Wiencke Island, Palmer Archipelago [*Gourdon*, 1908, p. 175]; analyst: Pisani.

50. Odinite (erratic), Mount Flora, Hope Bay, Louis Philippe Peninsula [*Bodman*, 1916, p. 58]; analyst: G. Bodman.

TABLE 2 (continued) – *Chemical analyses of rocks from Palmer Peninsula and outlying islands*

Item	51	52	53	54	55	56	57	58	59	60	61	62	63
SiO_2	54.24	53.73	53.50	53.45	53.03	53.02	52.93	52.85	52.83	52.65	52.02	51.94	51.56
TiO_2	0.91	0.81	1.65	0.66	0.06	1.16	2.29	1.60	0.90	0.89	1.40	...	1.34
Al_2O_3	17.20	19.38	17.62	19.37	15.78	15.57	15.86	19.17	19.38	17.79	18.26	14.92	17.95
Fe_2O_3	2.81	0.47	2.58	3.37	3.12	4.40	2.01	1.94	2.87	3.01	3.55	3.71	3.46
FeO	4.98	7.63	6.07	4.09	5.63	6.58	8.90	6.32	4.88	5.46	6.92	10.24	6.93
MnO	...	0.13	...	0.04	tr.	0.16	0.11	0.01	0.12	...	...	...	...
MgO	5.84	3.74	4.39	4.42	6.39	3.93	3.63	3.31	4.34	5.34	4.08	4.39	5.54
CaO	10.19	8.28	9.22	8.18	10.41	8.15	7.60	8.20	9.31	6.50	7.93	11.61	7.05
Na_2O	2.91	2.52	4.15	3.35	2.60	2.38	5.03	4.41	3.19	3.04	3.84	3.82	3.56
K_2O	0.92	1.91	0.75	1.35	0.69	1.68	0.64	1.38	1.72	4.06	0.31	0.39	1.28
H_2O+	0.09	0.65	0.00	1.69	1.44	2.02	0.42	0.59	0.45	0.95	1.44	0.19	1.58
H_2O-		0.10				0.50	0.04	0.08	0.07	...			
P_2O_5	0.09	0.56	0.36	...	...	0.35	0.35	0.11	0.27	0.18	0.51	...	0.10
CO_2	...	...	...	...	...	tr.	...	...	tr.	...	...	...	...
ZrO_2	...	...	...	...	...	...	...	...	...	...	...	...	...
Cl	...	...	...	...	...	...	...	...	...	...	...	...	...
F	...	...	...	...	...	...	...	...	...	...	...	...	...
S	...	...	...	...	...	...	0.06	...	...	...	...	...	...
SO_3	...	...	...	...	...	...	...	...	...	...	...	...	...
BaO	...	...	...	...	...	...	...	...	...	...	...	...	...
Cr_2O_3	...	...	...	...	...	...	...	...	...	...	...	...	...
(Ni,Co)O	...	...	...	...	...	...	...	...	...	...	...	...	...
Li_2O	...	...	...	...	...	...	...	...	...	...	...	...	...
	100.18	99.91	100.29	100.17	99.15	99.90	99.87	100.02	100.33	99.87	100.26	101.21	100.35

Item	64	65	66	67	68	69	70	71	72	73	74	75
SiO_2	51.16	50.98	50.68	50.66	50.55	50.54	50.22	49.84	49.68	49.48	49.29	48.97
TiO_2	0.07	1.25	1.40	...	1.32	0.89	1.95	1.32	0.28	0.79	1.99	1.62
Al_2O_3	16.12	17.60	20.47	19.70	18.44	17.30	16.20	19.37	9.84	18.00	16.65	16.12
Fe_2O_3	7.09	...	2.84	...	5.29	...	3.13	3.42	...	3.91	5.39	1.90
FeO	7.24	10.21	6.06	9.48	5.87	7.91	8.07	3.69	16.00	3.30	5.68	9.63
MnO	0.15	...	0.14	...	...	...	tr.	...	...	...	...	tr.
MgO	3.68	4.61	3.84	5.03	4.45	3.18	7.54	4.71	8.12	6.48	5.49	7.64
CaO	8.55	9.88	9.93	10.23	8.39	6.62	8.57	12.35	9.83	9.75	9.64	8.73
Na_2O	3.33	1.21	3.11	4.19	3.54	3.93	3.36	2.50	3.49	2.55	2.79	2.99
K_2O	0.57	1.93	0.53	1.16	0.53	3.53	1.38	0.87	0.67	0.66	0.79	1.21
H_2O+	1.52	0.98	0.51	0.71	1.23	1.20	0.22[a]	1.79	0.55	5.23	1.62	1.39[a]
H_2O-			0.08									
P_2O_5	0.96	...	0.45	...	0.35	...	...	0.11	...	0.17	0.46	...
CO_2	...	...	...	...	...	...	p	...	...	...	...	...
ZrO_2	...	...	...	...	...	...	...	...	...	...	...	...
Cl	...	...	...	...	...	...	...	...	...	...	...	...
F	...	...	...	...	...	...	...	...	...	...	...	...
S	...	...	...	...	...	...	...	...	...	...	...	...
SO_3	...	...	...	...	...	...	...	...	...	...	...	...
BaO	...	...	...	...	...	...	...	...	...	...	...	...
Cr_2O_3	...	...	...	...	...	...	...	...	...	...	...	...
(Ni,Co)O	...	...	...	...	...	...	...	...	...	...	...	...
Li_2O	tr.	...	...	...	...	...	...	...	...	...	...	...
	100.44	98.65	100.12	101.16	99.96	98.10	100.64	99.97	98.46	100.32	99.79	100.20

51. Olivine labradorite, Bridgman Island, South Shetland Islands [*Gourdon*, 1917, p. 7]; analyst: Boiteau.

52. Quartz-biotite diorite, Cape Bryant, Richard Black Coast [*Adie*, 1955, p. 24]; analyst: R. J. Adie.

53. Labradorite, Deception Island, South Shetland Islands [*Gourdon*, 1917, p. 7]; analysts: Lassieur and Boiteau.

54. Dolerite, Admiralty Bay, King George Island, South Shetland Islands [*Barth* and *Holmsen*, 1939, p. 25]; analyst: Brynjolf Bruun.

55. Gabbro, Anvers Island, Palmer Archipelago [*Pelikan*, 1909, p. 32]; analyst: Zdarek.

56. Tholeiitic basalt, Fildes Strait, King George Island, South Shetland Islands [*Tyrrell*, 1945, p. 59]; analyst: F. Herdsman.

57. Andesine basalt, Deception Island, South Shetland Islands [*Barth* and *Holmsen*, 1939, p. 11]; analyst: Brynjolf Bruun.

58. Dolerite (boulder), Port Lockroy, Wiencke Island, Palmer Archipelago [*Barth* and *Holmsen* 1939, p. 25]; analyst: Brynjolf Bruun.

59. Quartz gabbro, Last Hill, Louis Philippe Peninsula [*Adie*, 1955, p. 24]; analyst: R. J. Adie.

60. Diabase, Petermann Island, Dannebrog Islands group, off Graham Coast [*Washington*, 1917, p. 479]; analyst: Boiteau.

61. Augite andesite-labradorite, Jenny Island, off southeast coast of Adelaide Island [*Gourdon*, 1917, p. 9]; analyst: Lassieur.

62. Feldspar basalt, Mount Christen Christensen, Robertson Island, southward of the Nordenskjöld Coast [*Petersen*, 1895, p. 278]; analyst: J. Petersen.

63. Diabase, Jenny Island, off southeast coast of Adelaide Island [*Gourdon*, 1917, p. 9]; analyst: Lassieur.

64. Augite diorite, Moreno Island, Palmer Archipelago [*Pelikan*, 1909, p. 8]; analyst: Zdarek.

65. Titanite diorite, Hope Bay, Louis Philippe Peninsula [*Bodman*, 1916, p. 42]; analyst: G. Bodman.

66. Quartz gabbro, Terra Firma Islands, Marguerite Bay, off Fallieres Coast [*Adie*, 1955, p. 24]; analyst: R. J. Adie.

67. Olivine gabbro, Hope Bay, Louis Philippe Peninsula [*Bodman*, 1916, p. 45]; analyst: G. Bodman.

68. Andesite-labradorite, Jenny Island, off southeast coast of Adelaide Island [*Gourdon*, 1917, p. 9]; analyst: Lassieur.

69. Augite diorite (erratic), Snow Hill Island or Seymour Island, southeast of Louis Philippe Peninsula [*Bodman*, 1916, p. 39]; analyst: G. Bodman.

70. Basalt glass, Cockburn Island, southeast of Louis Philippe Peninsula [*Prior*, 1898, p. 89]; analyst: G. T. Prior.

71. Doleritic basalt, Deception Island, South Shetland Islands [*Gourdon*, 1917, p. 7]; analyst: Boiteau.

72. Uralitized olivine gabbro, East slope of The Pyramid, Hope Bay, Louis Philippe Peninsula [*Bodman*, 1916, p. 54]; analyst: G. Bodman.

73. Andesite-labradorite, Jenny Island, off southeast coast of Adelaide Island [*Gourdon*, 1917, p. 9]; analyst: Lassieur.

74. Doleritic basalt, Jenny Island, off southeast coast of Adelaide Island [*Gourdon*, 1917, p. 9]; analyst: Boiteau.

75. Basalt, Cockburn Island, southeast of Louis Philippe Peninsula [*Prior*, 1898, p. 89]; analyst: G. T. Prior.

TABLE 2 (concluded) – *Chemical analyses of rocks from Palmer Peninsula and outlying islands*

Item	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100
SiO_2	48.88	48.76	48.73	48.57	48.50	48.26	48.11	47.95	47.51	46.99	46.79	46.67	46.54	46.41	45.84	45.07	43.3	43.29	40.19	36.70	71.80	57.66	47.37	45.10	41.85
TiO_2	3.25	3.25	0.24	1.07	1.32	1.07	0.33	0.46	0.38	2.85	0.98	0.48	0.45	0.56	0.18	0.30	1.9	1.14	1.74	3.85	tr.	0.85	1.20	2.51	tr.
Al_2O_3	12.46	12.70	27.80	19.00	19.26	17.42	23.08	18.66	23.03	12.61	19.30	17.08	18.54	18.94	20.42	17.25	15.4	21.11	15.53	11.00	11.87	16.30	16.46	14.76	1.37
Fe_2O_3	3.77	4.23	2.11	...	4.24	3.36	2.29	...	1.08	3.21	3.67	...	...	...	6.51	1.92	1.7	4.98	8.88	14.21	2.21	3.46	1.92	4.50	2.62
FeO	8.09	7.41	1.34	7.39	5.26	5.61	3.28	8.08	4.00	8.94	...	8.87	10.37	10.35	6.64	6.37	10.3	7.50	8.99	12.24	2.30	2.46	7.41	9.87	2.16
MnO	0.15	0.21	nil	0.77	...	0.14	...	...	...	0.16	...	...	...	...	tr.	0.11	...	...	0.17	...	0.45	0.11	0.15	0.26	tr.
MgO	8.64	8.57	0.45	4.99	4.63	8.83	5.55	7.33	6.69	10.50	3.17	9.57	6.52	6.02	4.85	12.20	9.6	6.48	8.04	7.55	1.94	3.95	8.64	5.95	39.44
CaO	8.70	8.70	13.46	9.80	12.86	11.56	14.53	11.53	15.08	8.13	10.03	11.59	10.26	10.26	13.27	11.98	9.3	13.25	13.96	11.90	3.02	6.01	10.19	11.59	tr.
Na_2O	3.08	3.04	3.52	1.80	2.02	2.44	1.81	3.61	1.41	2.61	3.15	3.28	3.63	3.59	1.13	2.16	3.7	1.34	1.17	0.95	3.27	4.39	2.74	2.55	tr.
K_2O	1.55	1.53	0.43	2.70	1.06	0.89	0.23	1.32	0.22	1.09	0.50	0.69	1.57	1.54	0.23	0.37	1.4	0.26	0.03	0.22	1.02	2.68	0.06	0.47	0.13
H_2O+	0.15	0.33	2.06	0.62	0.50	0.24	0.88	2.24	0.98	1.00	1.18	0.71	3.27	2.84	1.27	2.04	3.9	0.17	0.69	1.36	1.29	0.98	3.38	0.26	11.03
H_2O-	0.67	0.66	0.20			0.16				1.30	0.40					0.08		...	0.10		0.48	0.10	0.10	0.10	0.45
P_2O_5	0.59	0.43	0.02	...	0.19	0.22	0.06	...	0.00	0.50	0.004	...	...	...	0.04	0.03	...	tr.	0.36	...	0.16	0.55	0.14	0.21	0.22
CO_2	0.00	0.00	nil	...	...	nil	...	...	...	0.00	6.19	...	...	...	...	nil	...	...	...	...	nil	0.12	0.21	1.38	nil
ZrO_2	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	0.00	0.00	...	...
Cl	0.14	0.08	...	...	...	...	...	...	...	0.09	...	...	...	...	...	0.09	...	...	...	...	...	0.02	0.00	...	...
F	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	p	0.00	...	...
S	0.01	0.02	...	...	...	...	...	...	...	0.02	...	...	...	...	...	0.18	...	...	...	...	0.08	0.19	0.02	0.23	...
SO_3	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	0.20	...
BaO	0.06	0.06	...	...	...	...	...	...	...	0.04	...	...	...	...	...	...	...	...	...	...	...	0.08	...	...	...
Cr_2O_3	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	0.12	...	...	...	...	...	...	...	...	0.19
(Ni,Co)O	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	nil	...	...	tr.	0.24
Li_2O	...	...	...	...	...	...	...	...	...	...	...	...	...	...	tr.	...	...	...	...	...	...	...	...	...	...
	100.19	99.91	100.36	96.71	99.84	100.20	100.15	101.18	100.38	100.04	100.07	98.94	101.15	100.51	100.38	100.15	100.5	100.52	100.05	99.98	99.89	99.91	99.99	99.94	99.70

76. Light-colored basalt, Peter I Island, northeast of Thurston Peninsula [*Brock*, 1927; p. 38] analyst: Emil Klüver.

77. Dark-colored basalt, Peter I Island, northeast of Thurston Peninsula [*Brock*, 1927, p. 38]; analyst: Emil Klüver.

78. Anorthositic band in eucrite, vicinity of Victor Hugo Island, off Graham Coast [*Barth* and *Holmsen*, 1939, p. 18]; analyst: Brynjolf Bruun.

79. Hornblende gabbro, Hope Bay, Louis Philippe Peninsula [*Bodman*, 1916, p. 48]; analyst: G. Bodman.

80. Gabbro, Jenny Island, off southeast coast of Adelaide Island [*Gourdon*, 1917, p. 9]; analyst: Boiteau.

81. Olivine basalt, lava of Recent volcano, Penguin Island, King George Bay, King George Island, South Shetland Islands [*Tyrrell*, 1945, p. 59]; analyst: F. Herdsman.

82. Gabbro, Webb Islet, off east coast of Adelaide Island [*Gourdon*, 1917, p. 10]; analyst: Boiteau.

83. Diabase, Hope Bay, Louis Philippe Peninsula [*Bodman*, 1916, p. 64]; analyst: G. Bodman.

84. Gabbro, Leonie Islet, Leonie Islets group, off southeast coast of Adelaide Island [*Gourdon*, 1917, p. 10]; analyst: Lassieur.

85. Porphyritic basalt, Peter I Island, northeast of Thurston Peninsula [*Brock*, 1927, p. 38]; analyst: Emil Klüver.

86. Carbonatized diabase, Port Lockroy, Wiencke Island, Palmer Archipelago [*Barth* and *Holmsen*, 1939, p. 24]; analyst: Brynjolf Bruun.

87. Uralitized olivine gabbro, small nunatak east of The Pyramid, Hope Bay, Louis Philippe Peninsula [*Bodman*, 1916, p. 51]; analyst: G. Bodman.

88. Serpentinized diabase, Hope Bay, Louis Philippe Peninsula [*Bodman*, 1916, p. 61]; analyst: G. Bodman.

89. Diabase, Hope Bay, Louis Philippe Peninsula [*Bodman*, 1916, p. 64]; analyst: G. Bodman.

90. Gabbro, Bob Island, off east coast of Wiencke Island, Palmer Archipelago [*Pelikan*, 1909, p. 40]; analyst: Zdarek.

91. Eucrite, vicinity of Victor Hugo Island, off Graham Coast [*Barth* and *Holmsen*, 1939, p. 19]; analyst: Brynjolf Bruun.

92. Amphibole basalt (erratic), Doumer Island, off Danco Coast [*Gourdon*, 1908, p. 192]; analyst: Pisani.

93. Gabbro, Petermann Island, Dannebrog Islands group, off Graham Coast [*Washington*, 1917, p. 553]; analyst: Lassieur.

94. Olivine gabbro, Terra Firma Islands, Marguerite Bay, off Fallieres Coast [*Adie*, 1955, p. 24]; analyst: R. J. Adie.

95. Uralitized gabbro, Cape Tuxen, Graham Coast [*Gourdon*, 1908, p. 159]; analyst: Pisani.

96. Garnet-albite schist, Lookout Harbor, Elephant Island, South Shetland Islands [*Tilley*, 1930, p. 60]; analyst: W. H. Herdsman.

97. Biotite-epidote-actinolite-albite schist (not very schistose), Clarence Island, South Shetland Islands [*Holtedahl*, 1929, p. 109]; analyst: Emil Klüver.

98. Chlorite-actinolite-clinozoisite-albite schist (very schistose), Clarence Island, South Shetland Islands [*Barth* and *Holmsen*, 1939, p. 60]; analyst: Emil Klüver.

99. Para-amphibolite, Lookout Harbor, Elephant Island, South Shetland Islands [*Tilley*, 1930, p. 61]; analyst: W. H. Herdsman.

100. Dunite-serpentine, Narrow Island, Gibbs Island group, south-southwest of Elephant Island (South Shetland Islands) [*Tyrrell*, 1945, p. 86]; analyst: F. Herdsman.

[a] Loss on ignition (mainly CO_2).

TABLE 3. *Chemical analyses of specimens from Marie Byrd Land—Victoria Land and vicinity*

Item	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
SiO_2	62.79	62.49	60.83	54.47	48.82	41.19	...	77.83	75.89	75.45	75.37	75.13	74.65	73.64	73.55	73.10	73.00	72.78	71.87	71.55	70.36	69.85
TiO_2	...	...	0.36	0.15	1.44	0.00	...	0.10	0.04	0.37	0.10	0.02	0.22	0.33	0.21	tr.	0.20	0.21	0.25	0.21	0.89	0.36
Al_2O_3	22.12	21.86	23.92	2.27	9.92	0.00	33.17	11.71	13.36	12.53	12.94	14.15	14.41	13.93	13.70	15.14	13.01	14.70	15.16	13.41	14.00	15.35
Fe_2O_3	0.36	0.30	0.11	0.58	2.20	0.82	...	0.11	0.89	0.45	0.06	0.07	0.52	0.90	0.24	0.06	0.13	0.27	0.62	1.60	0.77	0.40
FeO	0.41	1.31	2.14	5.37	6.37	7.26	13.57	1.24	0.18	1.67	1.48	0.89	1.08	1.40	2.36	0.16	1.08	1.18	2.10	1.26	3.32	3.88
MnO	...	...	...	0.09	0.12	0.11	...	0.02	0.01	...	0.02	0.02	0.02	tr.	0.05	tr.	0.01	0.03	0.04	tr.	0.08	0.06
MgO	...	0.16	0.07	33.86	10.60	50.10	18.00	tr.	0.06	0.14	0.07	0.07	0.50	0.30	0.26	0.15	0.62	0.42	0.29	0.64	1.29	0.52
CaO	3.76	3.74	3.39	2.11	18.22	0.06	...	0.63	0.27	0.70	0.73	0.35	2.63	0.96	0.92	1.18	0.63	0.99	0.84	2.46	2.09	2.94
Na_2O	7.35	7.20	6.11	...	1.53	0.10	...	3.11	4.78	4.43	3.23	4.07	4.36	5.17	3.59	3.96	4.04	3.01	3.88	3.46	2.98	3.13
K_2O	2.98	3.26	2.96	...	0.62	0.06	...	4.19	3.71	4.12	5.13	4.27	1.18	2.73	4.46	6.13	7.00	5.77	4.72	4.84	3.05	2.87
H_2O+	0.19	0.04	0.07	...	...	0.00	...	0.56	0.54	0.29	0.44	0.44	0.60	0.47	0.36	0.32	0.31	0.46	0.35	0.15	0.71	0.24
H_2O-	0.07	...	0.12	0.33	...	0.00	...	0.09	0.11	0.17	0.07	0.10	0.12	0.16	0.08	0.11	0.10	0.04	0.15	0.40	0.06	0.03
P_2O_5	...	...	...	...	...	...	...	0.06	0.08	...	0.02	0.09	0.06	...	...	0.05	0.31	0.20	tr.	0.08	0.21	0.50
CO_2	...	...	0.00	...	...	...	...	...	...	...	...	...	...	...	0.04	...	...	...	0.09	...	...	0.01
ZrO_2	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
Cl	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
F	...	...	...	...	...	...	...	0.15	...	...	0.15	0.15	...	...	...	...	...	...	...	...	...	...
S	...	...	...	...	...	...	...	...	...	...	...	...	0.08	...	...	0.10	0.08	...	...	...	...	...
SO_3	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
BaO	...	...	...	...	...	...	...	...	...	...	...	...	tr.	...	...	tr.	tr.	...	...	...	...	...
SrO	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
Cr_2O_3	...	...	...	...	0.16	...	34.51	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
$(Ce,Yt)_2O_3$	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
NiO	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
CoO	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
Li_2O	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
$O = F$	...	...	...	...	...	...	...	0.06	...	...	0.06	0.06	...	...	...	...	...	...	...	...	...	...
Less O	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
	100.03	100.36	100.08	99.84	100.00	99.70	99.25	99.74	99.92	100.32	99.75	99.76	100.43	99.99	99.82	100.46	100.52	100.06	100.36	100.06	99.81	100.14

1. Potash-oligoclase (type 1), Mount Erebus, Ross Island, Ross Archipelago [*Mountain*, 1925, p. 336]; analyst: E. D. Mountain.

2. Potash-oligoclase (type 2), Mount Erebus, Ross Island, Ross Archipelago [*Mountain*, 1925, p. 336]; analyst: E. D. Mountain.

3. Feldspar (anorthoclase), summit of Erebus, Ross Island, Ross Archipelago [*Jensen*, 1916, p. 122]; analysts: G. F. Burrows and A. B. Walkom.

4. Pyroxene phenocrysts from nodules (olivine fourchite), Volcano 116, Fosdick Mountains, Edsel Ford Ranges, Marie Byrd Land [*Fenner*, 1938, p. 375]; analyst: C. N. Fenner.

5. Groundmass pyroxene of olivine fourchite, Volcano 116, Fosdick Mountains, Edsel Ford Ranges, Marie Byrd Land [*Fenner*, 1938, p. 386]; analyst: C. N. Fenner.

6. Olivine phenocrysts from nodules (olivine fourchite), Volcano 116, Fosdick Mountains, Edsel Ford Ranges, Marie Byrd Land [*Fenner*, 1938, p. 375]; analyst: C. N. Fenner.

7. Picotite from olivine fourchite, Volcano 116, Fosdick Mountains, Edsel Ford Ranges, Marie Byrd Land [*Fenner*, 1938, p. 390]; analyst: C. N. Fenner.

8. Monzogranite, Rockefeller Mountains, Edward VII Peninsula [*Stewart*, 1934a, p. 153]; analyst: R. B. Ellestad.

9. Leucogranitic aplite, Rockefeller Mountains, Edward VII Peninsula [*Stewart*, 1934a, p. 153]; analyst: R. B. Ellestad.

10. Quartz-orthoclase porphyry, Dike C, The Flatiron, Granite Harbor, Victoria Land [*Smith*, 1924, p. 197]; analyst: E. D. Mountain.

11. Porphyritic leucomonzogranite, Rockefeller Mountains, Edward VII Peninsula [*Stewart*, 1934a, p. 153]; analyst: R. B. Ellestad

12. Alaskite, Rockefeller Mountains, Edward VII Peninsula [*Stewart*, 1934a, p. 153]; analyst: T. Kameda.

13. Plagioclase granite, Mount Betty, Victoria Land [*Schetelig*, 1915, p. 8]; analyst: N. Sahlbom.

14. Aplitic granite porphyry, Cape Irizar, Lamplugh Island, Victoria Land [*Mawson*, 1916, p. 218]; analyst: A. B. Walkom.

15. Quartz porphyry, near Mount Larsen, Victoria Land [*Mawson*, 1916, p. 216]; analyst: A. B. Walkom.

16. Aplitic granite, Mount Betty, Victoria Land [*Schetelig*, 1915, p. 7]; analyst: N. Sahlbom.

17. Granite, Scott Nunataks, Alexandra Mountains, Edward VII Peninsula [*Schetelig*, 1915, p. 15]; analyst: N. Sahlbom.

18. Leucogranite, one half way between Stations 1 and 2, Queen Maud Range, Victoria Land [*Stewart*, 1934a, p. 153]; analyst: T. Kameda.

19. Hornblende-biotite granite, Cape Irizar, Lamplugh Island, Victoria Land [*Mawson*, 1916, p. 211]; analyst: A. B. Walkom.

20. Biotite microgranite, intrusive into biotite diorite (erratic), Hell's Gate moraine, Terra Nova Bay region, Victoria Land [*Smith*, 1924, p. 207]; analyst: J. B. Plattnauer.

21. Tonalite, Mount Betty, Victoria Land [*Stewart*, 1934a, p. 153]; analyst: R. B. Ellestad.

22. Biotite granite, near Mount Larsen, Victoria Land [*Mawson*, 1916, p. 213]; analyst: A. B. Walkom.

TABLE 3 (continued) – *Chemical analyses of specimens from Marie Byrd Land—Victoria Land and vicinity*

Item	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44
SiO_2	69.67	69.62	68.33	68.00	64.57	64.13	62.54	61.01	58.94	58.93	58.90	58.64	57.95	57.33	56.09	55.95	55.93	55.80	55.63	55.62	55.47	54.92
TiO_2	1.18	0.45	0.29	0.16	0.53	0.65	0.69	...	1.40	1.25	1.29	0.28	0.40	0.96	1.23	0.98	0.64	1.01	1.33	1.35	1.32	1.31
Al_2O_3	13.26	14.80	16.56	17.28	16.92	14.32	15.41	16.62	16.33	18.16	16.24	22.55	20.43	18.14	20.79	22.53	19.61	18.22	16.92	19.07	20.67	19.53
Fe_2O_3	0.63	0.84	0.34	0.07	1.30	5.58	2.21	3.55	2.48	0.64	3.56	0.97	3.43	0.26	1.54	0.99	1.75	5.99	1.10	6.06	2.83	4.19
FeO	4.48	3.02	2.82	3.56	2.14	0.70	4.18	2.81	5.54	5.18	4.43	0.99	1.35	7.77	3.84	4.54	6.32	0.85	7.70	nil	1.86	1.74
MnO	tr.	tr.	tr.	0.05	0.05	0.12	tr.	0.55	0.21	0.07	0.18	tr.	0.07	tr.	0.05	tr.	0.13	0.24	0.11	0.20	0.02	0.21
MgO	1.37	0.89	0.61	0.37	1.71	0.72	2.53	0.06	1.03	2.92	0.77	0.16	0.26	3.05	1.26	tr.	0.50	1.17	2.34	1.20	1.43	1.07
CaO	8.96	3.14	3.43	1.67	4.09	2.36	5.60	3.27	2.10	6.14	2.27	1.43	1.90	5.61	3.18	3.21	3.53	2.78	8.03	2.72	3.43	3.48
Na_2O	0.24	3.19	3.85	4.08	4.52	5.29	2.39	5.92	5.54	3.42	5.60	9.87	8.32	3.11	7.33	7.42	7.75	8.13	3.41	7.56	8.33	7.48
K_2O	0.18	4.21	3.56	3.59	2.01	4.86	3.31	5.22	5.25	2.74	5.85	4.98	5.96	3.61	3.91	3.97	3.67	4.58	2.61	4.59	4.86	4.73
H_2O+	0.31	0.23	0.38	0.46	1.62	0.79[a]	0.62	1.13	0.42	0.56	0.28	0.35	0.39	0.39	0.39	0.00	0.19	nil	0.46	0.12	0.12	0.41
H_2O-	0.04	0.09	0.04	0.23	0.13		0.29	...	0.44	0.10	0.54	0.08	0.23	0.12	0.19	0.09	0.10	tr.	0.15	0.14	0.08	0.04
P_2O_5	tr.	tr.	0.23	tr.	0.17	0.39	0.25	tr.	0.57	...	0.12	tr.	0.07	...	0.38	...	0.12	0.50	0.27	0.57	0.03	0.26
CO_2	tr.	...	...	0.27	...	...	...	...	0.44	...	nil	...	...	0.02	...	0.02	...	0.04	...	0.03	...	nil
ZrO_2	...	...	...	...	...	...	...	...	0.22	...	0.02	...	...	...	...	...	...	0.12	...	0.15	...	0.03
Cl	...	...	...	..	...	...	...	tr.	...	...	...	...	...	...	0.17	...	...	0.20	...	...	...	0.26
F	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	0.07
S	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	0.06	0.08	...	...	0.12
SO_3	...	...	...	...	...	...	...	...	0.16	...	...	...	...	...	...	...	...	...	...	0.97	...	...
BaO	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	0.10	...	...	...	0.035
SrO	...	...	...	...	...	...	...	...	...	0.02	...	...	...	...	...	...	...	0.07	...	0.28	0.01	0.08
Cr_2O_3	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
$(Ce,Yt)_2O_3$	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	0.02	...	...	...	0.06
NiO	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	0.00	...	nil
CoO	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
Li_2O	...	...	...	...	...	...	...	...	0.00	...	...	...	...	...	...	...	...	nil	...	...	...	...
O = F	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
Less 0	...	...	...	...	...	...	...	...	...	...	0.033	...	...	...	...	...	...	0.07	...	...	...	0.14
	100.32	100.48	100.44	99.79	99.76	99.91	100.02	100.14	100.68	100.11	100.32[b]	100.30	100.76	100.37	100.35	99.61	100.24	99.81	100.14	100.53	100.46	99.90

23. Not named (erratic), Cape Royds, Ross Island, Ross Archipelago [*Washington*, 1917, p. 333]; analysts: G. J. Burrows and A. B. Walkom.

24. Quartz-orthoclase porphyry, Devil's Punchbowl, Granite Harbor, Victoria Land [*Smith*, 1924, p. 197]; analyst: J. B. Plattnauer.

25. Grey granite, Ridge Rocks, Cape Geology, Granite Harbor, Victoria Land [*Smith*, 1924, p. 170]; analyst: E. D. Mountain.

26. Granophyric granite porphyry (erratic), Cape Royds, Ross Island, Ross Archipelago [*Woolnough*, 1916, p. 175]; analysts: G. J. Burrows and A. B. Walkom.

27. Granodiorite, Mount Fridtjof Nansen, Victoria Land [*Stewart*, 1934a, p. 153]; analyst: R. B. Ellestad.

28. Phonolitic trachyte (rolled fragment), Possession Islands, off Victoria Land [*Prior*, 1902, p. 329]; analyst: G. T. Prior.

29. Hornblendic facies of grey granite, The Flatiron, Granite Harbor, Victoria Land [*Smith* 1924, p. 179]; analyst: J. B. Plattnauer.

30. Trachyte (waterworn pebble?), Cape Adare, Victoria Land [*David, Smeeth*, and *Schofield*, 1896, p. 473]; analyst: J. A. Schofield?.

31. Trachyphonolite, Mt. Cis, Ross Island, Ross Archipelago [*Jensen*, 1916, p. 122]; analyst: J. W. Hogarth.

32. Hornblende lamprophyre (Cuff Cape type), eastern end Cuff Cape, Granite Harbor, Victoria Land [*Smith*, 1924, p. 197]; analyst: E. D. Mountain.

33. Phonolitic trachyte (Mount Cis type), Mount Cis, Ross Island, Ross Archipelago [*Smith*, 1954, p. 37]; analyst: D. I. Bothwell.

34. Phonolitic trachyte, Brown Island, Ross Archipelago [*Prior*, 1907, p. 115]; analyst: G. T. Prior.

35. Trachyte, Cape Crozier, Ross Island, Ross Archipelago [*Prior*, 1907, p. 114]; analyst: G. T. Prior.

36. Not named (erratic), Cape Royds, Ross Island, Ross Archipelago [*Washington*, 1917, p. 447]; analysts: G. J. Burrows and A. B. Walkom.

37. Leucite kenyte, Cape Royds, Ross Island, Ross Archipelago [*Prior*, 1907, p. 113]; analyst: G. T. Prior.

38. Pumice, Mt. Erebus, Ross Island, Ross Archipelago [*Jensen*, 1916, p. 122]; analysts: G. J. Burrows and A. B. Walkom.

39. Trachydolerite, Scott Island, about 315 miles northeastward of Cape Adare, Victoria Land [*Prior*, 1907, p. 114]; analyst: G. T. Prior.

40. Pale kenyte 'inclusion,' The Ramp, Cape Evans, Ross Island, Ross Archipelago [*Smith*, 1954, p. 52]; analyst: K. Chaperlin.

41. Biotite diorite (erratic), Hell's Gate moraine, Terra Nova Bay region, Victoria Land [*Smith*, 1924, p. 207]; analyst: E. D. Mountain.

42. Kenyte, The Skuary, Ross Island, Ross Archipelago [*Jensen*, 1916, p. 122]; analyst: J. W. Hogarth.

43. Hornblende trachyte, Observation Hill, Ross Island, Ross Archipelago [*Prior*, 1907, p. 119]; analyst: G. T. Prior.

44. Kenyte, Deviation Hill, Cape Evans, Ross Island, Ross Archipelago [*Smith*, 1954, p. 52]; analyst: D. I. Bothwell.

TABLE 3 (continued) – *Chemical analyses of specimens from Marie Byrd Land—Victoria Land and vicinity*

Item	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66
SiO_2	54.84	54.27	54.17	54.17	54.16	53.64	53.26	53.06	52.67	52.54	52.41	51.91	51.35	50.71	49.58	48.26	48.22	47.56	47.40	46.98	45.63	45.61
TiO_2	1.34	1.33	0.73	0.64	0.70	0.82	0.70	1.60	0.43	1.44	0.55	2.34	0.79	2.71	0.60	0.88	2.09	2.60	0.63	2.94	2.42	3.48
Al_2O_3	18.57	19.23	19.92	14.90	15.08	14.56	15.64	18.65	13.17	19.41	15.53	20.75	18.90	17.08	13.58	22.67	18.47	18.77	20.27	16.75	10.43	15.70
Fe_2O_3	6.26	0.73	2.13	1.09	0.79	1.81	0.24	1.44	0.74	2.90	1.79	1.08	2.03	1.38	3.93	3.22	5.28	1.66	5.38	2.80	1.20	6.17
FeO	0.47	8.29	4.97	7.74	8.08	8.12	7.44	7.58	6.75	5.31	6.64	7.32	7.87	8.71	8.28	4.56	3.90	7.13	5.48	8.18	8.93	7.29
MnO	0.21	...	0.26	0.15	0.14	0.17	0.11	0.05	0.17	0.23	0.14	...	...	0.09	0.41	0.11	0.10	0.20	0.17	0.29	0.17	tr.
MgO	1.06	3.74	1.57	10.66	7.14	6.14	8.64	3.78	11.81	1.91	8.03	3.05	3.30	3.63	7.54	3.73	2.07	2.82	2.94	3.99	15.01	4.84
CaO	3.00	6.41	2.72	8.79	10.57	10.39	12.08	8.22	12.01	4.60	10.74	7.07	8.81	5.75	6.10	8.68	6.02	7.82	7.59	8.41	12.89	6.34
Na_2O	6.96	3.05	8.57	1.27	1.60	1.87	1.25	3.20	1.03	7.50	1.64	3.04	3.73	3.82	3.22	4.03	4.94	5.15	5.78	4.81	2.04	5.06
K_2O	4.51	2.49	4.85	0.54	1.11	0.50	0.58	1.55	0.39	3.49	0.62	2.44	1.48	3.63	1.25	2.15	3.47	2.68	2.73	1.97	0.74	2.67
H_2O+	1.20	0.77	0.20	0.53	0.36	1.65	0.41	0.94	0.57	0.16	1.36	0.58	0.97	1.75	3.83	0.32	2.89	1.27	0.23^{a}	1.28	0.16	2.34^{a}
H_2O-	0.62	0.18	nil	0.17	0.20	0.41	0.35	0.16	0.25	0.08	0.65	0.04	0.09	0.16	1.09	0.30	0.44	0.82		0.31	0.21	
P_2O_5	0.85	...	0.06	tr.	tr.	0.15	0.04	0.38	0.12	0.26	0.07	0.52	0.57	0.57	0.54	1.01	0.88	0.07	0.85	1.48	0.43	...
CO_2	0.05	0.05	nil	tr.	tr.	...	...	...	...	0.20	...	0.11	0.01	tr.	0.22	tr.	1.23^{d}	tr.	...	...	0.12	...
ZrO_2	0.20	...	nil	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	tr.	...	...
Cl	...	...	tr.	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
F	...	...	0.17	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
S	...	...	0.004	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
SO_3	0.56	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	0.06	...	...	...	...
BaO	...	...	0.03	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	0.04	...	...
SrO	...	...	nil	...	...	...	...	...	...	...	...	...	...	...	...	...	...	0.21	...	tr.	...	...
Cr_2O_3	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
$(Ce,Yt)_2O_3$	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
NiO	...	...	tr.	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
CoO	...	...	0.00	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
Li_2O	0.00	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
$O = F$	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
Less 0	...	...	0.08	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
	100.70	100.54	100.28^{c}	100.65	99.93	100.23	100.74	100.61	100.11	100.03	100.17	100.25	99.90	99.99	100.17	99.92	100.00	98.82	99.45	100.23	100.38	99.50^{e}

45. Vitrophyric kenyte, The Skuary, Ross Island, Ross Archipelago [*Jensen*, 1916, p. 122]; analyst: J. W. Hogarth.

46. Kersantite, Cape Irizar, Lamplugh Island, Victoria Land [*Mawson*, 1916, p. 221]; analyst: A. B. Walkom.

47. Kenyte pumice, Recent cinder cone of Mount Erebus, Ross Island, Ross Archipelago [*Smith*, 1954, p. 64]; analyst: J. D. Easton.

48. Porphyritic quartz dolerite with bronzite (erratic), Cape Royds, Ross Island, Ross Archipelago [*Benson*, 1916, p. 157]; analyst: W. N. Benson.

49. Aphanitic quartz dolerite (erratic), Cape Royds, Ross Island, Ross Archipelago [*Benson*, 1916, p. 157]; analyst: W. N. Benson.

50. Diabase, Mount Fridtjof Nansen, Queen Maud Range, Victoria Land [*Stewart*, 1934a, p. 153]; analyst: T. Kameda.

51. Dolerite, Knobhead, Victoria Land [*Prior*, 1907, p. 137]; analyst: G. T. Prior.

52. Basic diorite or hornblende gabbro, Cathedral Rocks, Victoria Land [*Prior*, 1907, p. 127]; analyst: G. T. Prior.

53. Gabbro, Mount Fridtjof Nansen, Queen Maud Range, Victoria Land [*Stewart*, 1934a, p. 153]; analyst: R. B. Ellestad.

54. Phyrohornblende trachyte, Cape Bird, Ross Island, Ross Archipelago [*Jensen*, 1916, p. 122]; analysts: G. J. Burrows and A. B. Walkom.

55. Melabasalt, Mount Fridtjof Nansen, Queen Maud Range, Victoria Land [*Stewart*, 1934a, p. 153]; analyst: R. B. Ellestad.

56. Sphene-biotite-hornblende diorite (erratic), near Mount Larsen, Victoria Land [*Mawson*, 1916, p. 225]; analyst: A. B. Walkom.

57. Biotite-hornblende diorite (erratic), near Mount Larsen, Victoria Land [*Mawson*, 1916, p, 225]; analyst: A. B. Walkom.

58. Augite-biotite kersantite, G_1, Northern Foothills, Victoria Land [*Prior*, 1907, p. 130]; analyst: G. T. Prior.

59. Hornblende lamprophyre (spessartite), Dike Z, Cuff Cape, Granite Harbor, Victoria Land [*Smith*, 1924, p. 197]; analyst: E. D. Mountain.

60. Kulaitic basalt, Cape Bird, Ross Island, Ross Archipelago [*Jensen*, 1916, p. 122]; analysts: G. J. Burrows and A. B. Walkom.

61. Banakite-like rock, G_3, Northern Foothills, Victoria Land [*Prior*, 1907, p. 132]; analyst: G. T. Prior.

62. Plagioclase kenyte, Turk's Head, Ross Island, Ross Archipelago [*Jensen*, 1916, p. 122]; analyst: J. W. Hogarth.

63. Hornblende basalt, foot of Mount Terror, Ross Island, Ross Archipelago [*Prior*, 1902, p. 326]; analyst: G. T. Prior.

64. Basalt, summit of Little Razorback Island, Ross Archipelago [*Smith*, 1954, p. 99]; analyst: D. I. Bothwell.

65. Limburgite, Mount Erebus, Ross Island, Ross Archipelago [*Jensen*, 1916, p. 122]; analysts: G. J. Burrows and A. B. Walkom.

66. Basalt, Franklin Island, off Victoria Land [*Prior*, 1898, p. 80]; analyst: G. T. Prior.

TABLE 3 (concluded)—*Chemical analyses of specimens from Marie Byrd Land—Victoria Land and vicinity*

Item	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88
SiO_2	45.26	45.13	43.92	43.54	43.17	42.92	42.14	42.10	41.64	41.47	78.54	76.01	67.34	22.19	74.67	73.11	71.70	71.43	69.89	69.76	64.51	47.07
TiO_2	3.09	...	4.19	5.03	1.26	3.77	4.90	4.93	4.36	5.19	0.65	0.31	0.89	0.55	1.10	1.66	1.11	...	0.68	0.38	0.82	1.62
Al_2O_3	16.93	18.13	17.42	16.08	13.80	15.34	14.95	14.87	13.80	14.31	10.81	13.29	15.52	6.05	8.37	7.11	6.90	11.03^{i}	13.14	15.15	16.87	15.45
Fe_2O_3	2.85	12.94	4.09	2.63	3.65	3.71	2.90	3.26	7.93	3.96	0.35	0.52	0.63	1.30	0.95	0.26	0.96	1.81	0.43	0.87	1.33	6.65
FeO	8.79	...	8.83	10.14	8.99	10.39	9.71	9.76	5.41	11.48	1.42	1.75	4.87	1.55	3.37	3.45	3.74	2.56	5.61	2.51	4.06	6.50
MnO	0.29	...	0.09	0.20	0.20	0.23	0.12	0.07	0.19	0.22	0.06	0.01	0.04	...	0.09	...	0.05	0.52	0.43	0.07	0.07	0.22
MgO	3.98	7.33	4.89	6.44	11.32	7.25	9.47	8.88	8.78	7.07	0.80	0.60	2.01	1.98	2.52	3.48	2.82	2.44	2.82	1.25	2.58	6.49
CaO	9.32	11.23	9.53	8.09	8.95	10.98	10.32	10.63	11.16	10.03	0.73	0.72	0.40	34.44	5.19	6.06	11.37	4.07	0.37	3.20	0.94	10.29
Na_2O	4.58	2.14	4.60	3.61	4.02	3.15	3.27	3.20	2.14	3.13	3.32	3.33	1.59	1.96	2.09	1.89	0.66	2.10	1.81	3.53	1.35	1.17
K_2O	2.04	0.98	2.17	1.67	1.76	1.30	1.80	1.80	1.40	1.59	2.08	2.63	3.44	2.51	1.31	2.51	0.10	2.77	3.21	2.42	5.17	1.82
H_2O+	0.77	2.18	0.11	0.36	0.76	0.35	0.16	0.12	0.47	0.57	0.95	0.25	2.93	0.92	0.30	0.42	0.22	1.44	1.31	0.59	1.75	0.87
H_2O-	0.20		0.06	0.08	0.12	nil	0.12	0.11	0.62	0.36	0.09	0.27	0.17	0.46	0.26	0.11	0.08	...	0.04	0.05	0.03	0.25
P_2O_5	1.66	...	0.67	1.29	0.77	tr.	0.40	0.58	0.96	0.49	0.15	0.37	0.15	...	0.57	tr.	0.09	...	0.10	0.14	0.22	0.80
CO_2	...	...	...	0.15	1.25	0.08	...	...	0.05	...	...	0.06	...	26.55	...	...	tr.	...	...	...	...	...
ZrO_2	tr.	...	...	...	0.01	0.03	...	...	0.00	0.005	...	...	...	...	tr.	...	...	...	...	...	...	...
Cl	...	...	...	...	0.02	...	...	...	...	...	...	...	...	...	...	...	0.16	tr.	...	...	...	...
F	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	tr.	...	...	...	...
S	...	...	...	...	0.15	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	0.55
SO_3	...	...	...	...	...	...	...	...	1.70	...	...	...	...	...	...	...	...	...	...	...	...	...
BaO	0.05	...	...	...	0.06	0.057	...	...	0.00	0.04	...	...	...	...	...	...	...	...	...	...	...	tr.
SrO	tr.	...	...	1.46	...	0.06	...	...	...	0.08	...	...	...	...	...	...	...	...	...	...	...	...
Cr_2O_3	...	...	...	...	0.09	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
$(Ce,Yt)_2O_3$	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
NiO	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
CoO	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
Li_2O	...	...	...	...	...	...	...	...	0.00	...	...	...	...	...	...	...	...	...	...	...	...	...
O = F	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
Less 0	...	...	...	...	0.07	...	...	...	...	...	...	...	...	...	...	...	0.04	...	...	...	...	...
	99.81	100.06	100.57	100.77	100.28	99.9^{f}	100.26	100.31	100.61	101.2^{g}	99.95	100.12	99.98^{h}	100.46	100.79	100.06	99.92	100.17	99.84	99.92	99.70	99.75

67. Basalt, Middle Dome, Cape Barne, Ross Island, Ross Archipelago [*Smith*, 1954, p. 99]; analyst: D. I. Bothwell.

68. Olivine basalt (pebble), Cape Adare, Victoria Land [*David*, *Smeeth*, and *Schofield*, 1896, pp. 477–478]; analyst: J. A. Schofield?.

69. Hornblende basalt, Sulphur Cones, Ross Island, Ross Archipelago [*Prior*, 1907, p. 103]; analyst: G. T. Prior.

70. Olivine basalt, Cape Barne, Ross Island, Ross Archipelago [*Jensen*. 1916, p. 122]; analyst: J. W. Hogarth.

71. Aphanitic groundmass of olivine fourchite with microphenocrysts of olivine distributed through it, Volcano 116, Fosdick Mountains, Edsel Ford Ranges, Marie Byrd Land [*Fenner*, 1938, p. 375]; analyst: C. N. Fenner.

72. Olivine basalt, Taylor Valley, Ferrar Glacier region, Victoria Land [*Smith*, 1954, p. 84]; analysts: N. E. Butcher and D. I. Bothwell.

73. Olivine basalt, near The Gap, Ross Island, Ross Archipelago [*Prior*, 1907, p. 105]; analyst: G. T. Prior.

74. Limburgite-like rock, Ridge Road, near Winter Quarters, Ross Island, Ross Archipelago [*Prior*, 1907, p. 105]; analyst: G. T. Prior.

75. Leucite tephrite, Crater Hill, Ross Island, Ross Archipelago [*Jensen*, 1916, p. 122]; analyst: J. W. Hogarth.

76. Olivine basalt, lava flow, Black Hill, Taylor Valley, Ferrar Glacier region, Victoria Land [*Smith*, 1954, p. 84]; analyst: D. I. Bothwell.

77. Arkose, Mount Fridtjof Nansen, Queen Maud Range, Victoria Land [*Stewart*, 1934a, p. 153; 1934f, p. 356]; analyst: R. B. Ellestad.

78. Arkose, Upper Glacier Depot, Beardmore Glacier, Victoria Land [*Mawson*, 1916, p. 207]; analysts: G. J. Burrows and A. B. Walkom.

79. Micaceous arkose, Mount Fridtjof Nansen, Victoria Land [*Stewart*, 1934f, p. 356]; analyst: R. B. Ellestad.

80. Limestone, 'Farthest South,' Victoria Land [*Skeats*, 1916, p. 197]; analyst: F. L. Stillwell.

81. Pyroxene granulite (erratic), Cape Royds, Ross Island, Ross Archipelago [*Walkom*, 1916, p. 161]; analysts: G. J. Burrows and A. B. Walkom.

82. Para-pyroxene granulite from inclusion in grey granite: center of spheroid, Point K, The Flatiron, Granite Harbor, Victoria Land [*Smith*, 1924, p. 179]; analyst: E. D. Mountain.

83. Pyroxene granulite (erratic), Cape Royds, Ross Island, Ross Archipelago [*Walkom*, 1916, p. 161]; analysts: G. J. Burrows and A. B. Walkom.

84. Mica schist, Cape Adare, Victoria Land [*David*, *Smeeth*, and *Schofield*, 1896, p. 482]; analyst: J. A. Schofield?.

85. Biotite schist, Supporting Party Mountain, Queen Maud Range, Marie Byrd Land [*Stewart*, 1934a, p. 154]; analyst: R. B. Ellestad.

86. Oligoclase-biotite gneiss, O'Brien Peak, Queen Maud Range, Victoria Land [*Stewart*, 1934a p. 154]; analyst: R. B. Ellestad.

87. Muscovite-biotite schist, southeast of Station 1, Queen Maud Range, Victoria Land [*Stewart*, 1934a, p. 154]; analyst: R. B. Ellestad.

88. Amphibolite, Scott Nunataks, Alexandra Mountains, Edward VII Peninsula [*Schetelig*, 1915, p. 23]; analyst: N. Sahlbom.

[a] Ignition.

[b] Includes F, 0.04; Cl, 0.07; S″, nil; $(Ce, Yt)_2O_3$, 0.09; BaO, 0.057; Li_2O, Cr_2O_3, V_2O_3, and CaO, nil; MoO_3, 0.0011; CuO, 0.017; ZnO, 0.006; PbO, 0.0027; NiO, 0.002.

[c] Includes PbO, 0.006; CuO, 0.002; MoO_3, trace.

[d] CO_2 and loss.

[e] SnO_2, trace.

[f] Includes S″, 0.10; Cl, 0.10; F, 0.20; also heavy metals.

[g] Includes S″, 0.27; Cl, 0.14; P″, 0.11.

[h] Ellestad records a slight, black, insoluble residue which is undoubtedly carbon.

[i] Included P_2O_5 (?).

TABLE 4 – *Chemical analyses of specimens from George V Coast and vicinity*

Item	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
SiO_2	65.02	64.92	62.72	53.66	51.36	47.96	47.96	45.92	77.95	76.99	76.50	76.34	73.52	72.50	53.05	72.38
TiO_2	0.00	0.00	0.00	0.04	0.08	0.00	0.00	...	nil	0.13	0.13	ft. tr.	0.23	0.35	0.65	0.40
Al_2O_3	18.88	19.36	23.66	0.79	2.57	31.52	31.52	35.34	14.04	12.62	13.12	13.48	14.92	14.40	16.95	13.39
Fe_2O_3	0.60	0.00	...	nil	nil	1.03	1.03	1.05	0.36	0.70	0.87	0.39	0.25	0.86	0.79	0.73
FeO	0.54	m. tr.[a]	0.03	2.70	4.32	3.24	3.24	...	0.13	0.25	0.45	0.29	1.31	0.97	6.69	1.09
MnO	0.01	m. tr.[a]	0.00	0.38	0.43	1.09	1.09	...	nil	tr.	0.15	tr.	0.07	st. tr.	0.07	tr.
MgO	0.10	0.05	0.00	17.14	15.98	12.16	12.16	s. tr.	0.35	tr.	0.68	0.03	st. tr.	0.98	6.91	0.67
CaO	0.01	0.00	2.44	24.26	24.44	0.00	0.00	16.39	tr.	0.76	0.38	0.85	1.38	1.03	11.56	1.86
Na_2O	2.47	1.59	8.76	0.10	0.40	0.33	0.33	1.70	6.33	2.37	2.68	2.73	2.86	2.95	2.05	2.02
K_2O	11.08	13.63	1.57	0.25	0.05	tr.	tr.	0.20	0.38	5.87	4.91	5.43	5.22	4.88	0.97	6.57
H_2O+	0.88	0.24	1.04	0.92	0.72	2.80	2.80	0.33	0.25	0.38	0.66	0.58	0.56	0.84	0.49	0.44
H_2O-								0.00	0.08	0.10	0.14	0.09	0.13	0.13	0.43	0.12
P_2O_5	...	...	...	nil	nil	tr.	tr.	...	tr.	nil	tr.	tr.	ft. tr.	0.08	tr.	0.16
CO_2	...	...	...	nil	nil	...	...	...	nil	nil	nil	st. tr.	nil	st. tr.	...	...
ZrO_2	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
Cl	...	...	...	...	...	...	...	...	tr.	tr.	tr.	st. tr.	tr.	tr.	...	nil
S	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
SO_3	...	...	...	...	...	...	...	...	nil	nil	nil	nil	nil	nil	...	nil
BaO	0.13	0.39	tr.	nil	nil	tr.	tr.	...	...	...	...	...	...	...	...	...
SrO	p[b]	p[b]	p[b]	nil	nil	tr.	p[b]	...	...	...	...	...	...	...	...	...
Cr_2O_3	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
NiO, CoO	...	...	...	...	...	...	...	...	nil	nil	nil	nil	nil	nil	...	...
CoO	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
Li_2O	0.00	0.00	p[b]	p[b]	p[b]	p[b]	p[b]	...	st. tr.	ft. tr.	nil	tr.	tr.	tr.	...	tr.
O = Cl	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
O = S	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
	99.72	100.18	100.22	100.24	100.35	100.13	100.13	100.93	99.87	100.17	100.67	100.21	100.45	99.97	100.61	99.83

1. Red orthoclase in pegmatitic schlier in red granite (erratic), Cape Denison, Commonwealth Bay, George V Coast [*Mawson*, 1940b, p. 381]; analyst J. C. H. Mingaye.

2. Adularia in a coarse pegmatitic band in a biotite-sillimanite gneiss (erratic); Cape Denison, Commonwealth Bay, George V Coast [*Mawson*, 1940b, p. 382]; analyst: J. C. H. Mingaye.

3. Oligoclase, partly sericitised, etc., in quartz reef, 200 yards east of anemometer site, Cape Denison, Commonwealth Bay, George V Coast [*Mawson*, 1940b, p. 385]; analyst: H. P. White.

4. Grey-green diopside from diopside-actinolite gneiss (erratic), Cape Denison, Commonwealth Bay, George V Coast [*Mawson*, 1940b, p. 386; *Glastonbury*, 1940e, p. 315]; analyst: J. C. H. Mingaye.

5. Green diopside from pyroxene-epidote-garnet rock (erratic); Cape Denison, Commonwealth Bay, George V Coast [*Mawson*, 1940, p. 386]; analyst: H. P. White.

6. Cordierite from garnet-biotite-sillimanite gneiss (erratic), Cape Denison, Commonwealth Bay, George V Coast [*Tilley*, 1940a, p. 340]; analyst: H. P. White.

7. Cordierite from cordierite-sillimanite-quartz-feldspar composite gneiss (erratic); Cape Denison, Commonwealth Bay, George V Coast [*Mawson*, 1940b, p. 390]; analyst: J. C. H. Mingaye.

8. Calcic feldspar from augite amphibolite (erratic), Cape Denison, Commonwealth Bay, George V Coast [*Stillwell*, 1923, p. 265]; analyst: J. C. Watson.

9. Graphic granite (runite) (erratic), Cape Denison, Commonwealth Bay, George V Coast [*Summers* and *Edwards*, 1940; p. 89]; analysts: P. G. W. Bayly and J. C. Watson.

10. Fine-grained granite (erratic), Cape Denison, Commonwealth Bay, George V Coast [*Summers* and *Edwards*, 1940, p. 89); analysts: P. G. W. Bayly and J. C. Watson.

11. Pink granite (erratic), Cape Denison, Commonwealth Bay, George V Coast [*Summers* and *Edwards*, 1940, p. 89]; analysts: P. G. W. Bayly and J. C. Watson.

12. Grey granite (erratic), Cape Denison, Commonwealth Bay, George C Coast [*Summers* and *Edwards*, 1940, p. 89]; analysts: P. G. W. Bayly and J. C. Watson.

13. Pink granite (erratic); Cape Denison, Commonwealth Bay, George V Coast [*Summers* and *Edwards*, 1940, p. 89]; analysts: P. G. W. Bayly and J. C. Watson.

14. Grey biotite (erratic), Cape Denison, Commonwealth Bay, George V Coast [*Summers* and *Edwards*, 1940, p. 89]; analysts: P. G. W. Bayly and J. C. Watson.

15. Dolerite, Horn Bluff, George V Coast [*Browne*, 1923, p. 253]; analysts: G. D. Osborne and M. L. Graham.

16. Hypersthene-alkali feldspar gneiss, Madigan Nunatak, George V Coast [*Stillwell*, 1918, p. 135]; analyst: J. C. Watson.

TABLE 4 (Concluded) – *Chemical analyses of specimens from George V Coast and vicinity*

Item	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33
SiO_2	69.42	67.10	60.93	57.78	55.39	53.73	52.73	50.62	50.35	49.99	49.91	48.74	48.06	47.74	45.49	43.12	24.96
TiO_2	0.35	0.68	1.07	0.73	0.86	1.14	2.14	1.42	0.49	1.78	2.39	1.26	2.54	1.83	2.29	1.35	0.20
Al_2O_3	15.03	14.87	18.09	12.01	18.36	11.57	13.99	11.43	16.18	13.84	13.02	13.64	14.19	15.10	19.50	12.74	20.76
Fe_2O_3	1.66	1.14	1.88	7.35	1.76	13.15	4.31	4.43	13.57	1.97	2.84	3.31	1.95	2.47	9.13	1.35	3.24
FeO	2.65	3.76	5.55	4.98	6.81	14.41	9.19	11.11	5.57	13.18	13.70	9.98	15.66	12.43	0.64	10.14	21.86
MnO	0.06	tr.	0.14	8.23	0.24	0.24	0.39	0.28	4.12	0.07	0.12	0.35	...	0.24	0.05	0.13	0.05
MgO	1.10	1.80	4.54	1.79	4.74	2.11	3.27	6.87	1.78	6.01	4.74	7.12	5.29	6.85	0.45	17.13	18.18
CaO	3.45	3.47	0.90	2.85	2.79	1.79	5.98	10.90	1.94	9.72	9.28	10.34	9.24	9.41	16.88	4.70	nil
Na_2O	4.50	2.56	1.78	1.70	3.36	0.15	1.73	1.75	3.14	1.94	2.03	1.96	0.71	2.09	2.66	0.26	nil
K_2O	1.39	3.50	3.89	1.47	3.74	0.00	2.98	0.24	0.89	0.79	0.83	0.83	1.29	0.61	0.30	6.08	nil
H_2O+	0.65	0.68	1.15	0.69	1.46	0.80	1.72	0.62	0.50	1.40	0.87	1.95	1.21	0.73	0.08	3.07	11.45
H_2O-	0.07	0.11	0.14	0.52	0.13	0.62	0.10	0.19	0.98	0.05	0.12	0.11	0.13	0.19	1.25	0.02	0.19
P_2O_5	tr.	0.20	tr.	0.16	0.14	0.53	0.90	0.08	0.48	tr.	0.20	0.14	0.28	0.30	0.87	tr.	nil
CO_2	nil	nil	...	...	...	0.00	st. tr.	...	0.00	tr.	tr.	tr.	...	...	nil	nil	nil
ZrO_2	...	...	...	0.06	...	tr.	nil	...	tr.	...	...	nil	...	...	...	...	...
Cl	tr.	0.05	tr.	...	tr.	...	0.08	tr.	...	st. tr.	tr.	0.04	...	tr.	0.02	0.06	tr.
S	...	...	...	0.00	...	0.16	0.04	...	tr.	...	...	0.06	...	...	...	...	...
SO_3	nil	nil	nil	0.00	nil	0.00	nil	nil	...	nil	nil	nil	...	nil	tr.	nil	tr.
BaO	...	...	...	tr.	...	0.00	0.05	...	0.00	...	...	nil	...	...	...	...	...
SrO	...	...	...	0.06	...	0.00	...	...	tr.	...	...	...	...	...	...	...	...
Cr_2O_3	...	...	...	0.00	...	0.00	0.03	...	0.00	...	...	0.05	...	...	...	...	...
NiO, CoO	...	tr.	0.02	tr.	0.03	0.00	0.03	0.03	0.00	0.01	0.01	0.01	...	0.02	0.02	tr.	tr.
CoO	...	nil	tr.	...	tr.	...	tr.	tr.	...	p	p	tr.	...	p	nil	p	nil
Li_2O	st. tr.	tr.	st. tr.	...	tr.	...	tr.	tr.	...	tr.	st. tr.	tr.	...	tr.	st. tr.	nil	nil
O = Cl	...	...	...	...	...	...	0.02	...	...	...	...	0.01	...	...	...	...	...
O = S	...	...	...	...	...	...	0.01	...	...	...	...	0.02	...	...	...	...	...
	100.33	99.92	100.08	100.38	99.81	100.40	99.63	99.97	99.99	100.75	100.06	99.86	100.05	100.01	99.63	100.15	100.89

17. Hypersthene-alkali feldspar gneiss, Aurora Peak, George V Coast [*Stillwell*, 1918, p. 140]; analyst: J. C. Watson.

18. Granodiorit2 gneiss, Hut site, Cape Denison, Commonwealth Bay, George V Coast [*Stillwell*, 1918, p. 86]; analyst: J. C. Watson.

19. Garnet-cordierite gneiss, Cape Gray, Commonwealth Bay, George V Coast [*Stillwell*, 1918, p. 152]; analyst: A. G. Hall.

20. Garnet-magnetite schist (erratic), Cape Denison, Commonwealth Bay, George V Coast [*Coulson*, 1925, p. 292]; analyst: A. L. Coulson.

21. Kyanite-biotite gneiss, Cape Garnet, George V Coast [*Stillwell*, 1918, p. 152]; analyst: A. G. Hall.

22. Garnet-quartz-magnetite rock (erratic), Cape Denison, Commonwealth Bay, George V Coast [*Coulson*, 1925, p. 292]; analyst: A. L. Coulson.

23. Epidote-biotite schist, Cape Denison, Commonwealth Bay, George V Coast [*Stillwell*, 1918, pp. 41–42); analyst: A. G. Hall.

24. Plagioclase-pyroxene gneiss (pyroxene granulite); Madigan Nunatak, George V Coast [*Stillwell*, 1918, p. 131]; analyst: A. G. Hall.

25. Porphyroblastic magnetite-garnet gneiss (erratic), Cape Denison, Commonwealth Bay, George V Coast [*Coulson*, 1925, p. 292]; analyst: A. L. Coulson.

26. Garnet amphibolite, Cape Garnet, George V Coast [*Stillwell*, 1918, p. 183]; analysts: P. G. W. Bayly and J. C. Watson.

27. Hornblende-plagioclase-pyroxene gneiss, Cape-Pigeon Rocks, George V Coast [*Stillwell*, 1918, p. 183]; analysts: P. G. W. Bayly and J. C. Watson.

28. Amphibolite, Cape Denison, Commonwealth Bay, George V Coast [*Stillwell*, 1918, pp. 41–42]; analyst: A. G. Hall.

29. Garnet amphibolite, Stillwell Island, Way Archipelago, off George V Coast [*Stillwell*, 1918, p. 183]; analysts: P. G. W. Bayly and J. C. Watson.

30. Plagioclase-pyroxene gneiss, Cape Gray, Commonwealth Bay, George V Coast [*Stillwell*, 1918, p. 183]; analysts: P. G. W. Bayly and J. C. Watson.

31. Epidosite, Cape Denison, Commonwealth Bay, George V Coast [*Stillwell*, 1918, p. 63]; analyst: J. C. Watson.

32. Biotite-hornblende schist, Cape Denison, Commonwealth Bay, George V Coast [*Stillwell*, 1918, p. 59]; analyst: J. C. Watson.

33. Chlorite rock, Cape Dennison, Commonwealth Bay, George V Coast [*Stillwell*, 1918, p. 63]; analyst: J. C. Watson.

[a] Less than 0.01 pct.

[b] Spectroscopic.

TABLE 5.—*Chemical analyses of specimens from Wilhelm II, and Mac-Robertson Coasts and Enderby Land*

Item	1	2	3	4	5	6	7	8	9	10	11	12	13
SiO_2	75.50	74.23	51.43	51.20	50.53	50.08	49.60	48.71	47.77	47.52	83.24	73.84	56.60
TiO_2	0.08	0.39	1.12	1.23	0.80	...	1.01	1.34	...	...	tr.	0.09	0.92
Al_2O_3	13.92	12.16	14.88	14.47	14.62	15.48	14.30	13.26	8.18	1.18	7.96	14.06	18.56
Fe_2O_3	0.48	0.96	6.30	6.76	6.82	2.16	6.91	7.35	4.20	1.19	tr.	tr.	0.63
FeO	1.17	2.34	3.14	2.94	2.88	5.04	3.05	6.02	6.13	9.48	3.46	1.55	7.64
MnO	nil	tr.	...	...	...	...	...	...	...	...	0.13	nil	0.06
MgO	0.52	0.43	6.67	6.19	6.16	4.65	6.54	5.89	12.03	39.20	0.77	0.41	5.02
CaO	3.54	1.74	5.01	4.81	5.00	5.51	5.45	4.65	14.15	0.61	2.02	1.65	5.27
Na_2O	3.64	2.44	1.83	2.01	1.70	2.62	1.97	2.10	0.61	0.42	1.31	2.72	2.11
K_2O	0.74	4.62	9.22	9.50	8.32	14.37	8.78	9.96	7.53		0.45	5.08	1.93
H_2O+	0.15	0.40	0.74	0.86	0.90	...	0.93	1.03	...	...	0.40	0.25	0.60
H_2O-	0.30	0.38				...			...	...	0.40	0.25	0.45
P_2O_5	nil	0.08	0.51	0.70	0.62	...	0.50	0.36	...	...	tr.	nil	0.37
CO_2	...	...	...	...	...	...	...	...	...	...	...	nil	nil
Cr_2O_3	...	...	...	...	...	...	...	...	...	0.21	...	...	...
	100.04	100.17	100.85	100.66	99.35	99.91	99.63	100.66	100.60	99.81	100.14	99.90	100.16

1. Enderbite, Proclamation Island, off Enderby Land [*Tilley*, 1936; p. 314]; analyst: C. E. Tilley.
2. Charnockite, Proclamation Island, off Enderby Land [*Tilley*, 1937a; p. 6]; analyst: C. E. Tilley.
3. Leucite basalt, variety 2, Mount Gauss, Wilhelm II Coast [*Reinisch*, 1906; p. 81]; analyst: R. Reinisch.
4. Leucite basalt, variety 4, Mount Gauss, Wilhelm II Coast [*Reinisch*, 1906; p. 81]; analyst: R. Reinisch.
5. Leucite basalt, variety 1, Mount Gauss, Wilhelm II Coast [*Reinisch*, 1906; p. 81]; analyst: R. Reinisch.
6. Augite-leucite segregation, Mount Gauss, Wilhelm II Coast [*Reinisch*, 1906; p. 84]; analyst: R. Reinisch.
7. Leucite basalt, variety 3, Mount Gauss, Wilhelm II Coast [*Reinisch*, 1906; p. 81]; analyst: R. Reinisch.
8. Glass crust of vesicle, Mount Gauss, Wilhelm II Coast [*Reinisch*, 1906; p. 81]; analyst: R. Reinisch.
9. Olivine-rich leucite-augite segregation, Mount Gauss, Wilhelm II Coast [*Reinisch*, 1906; p. 84]; analyst: R. Reinisch.
10. Olivine segregation; Mount Gauss, Wilhelm II Coast [*Reinisch*, 1906; p. 84]; analyst: R. Reinisch.
11. Quartz-andesine-garnet gneiss, First Landing, Cape Bruce, Mac-Robertson Coast [*Tilley*, 1937b; p. 24]; analyst: C. E. Tilley.
12. Garnet granulite, Proclamation Island, off Enderby Land [*Tilley*, 1937a; p. 10]; analyst: C. E. Tilley.
13. Garnet-biotite-plagioclase orthogneiss, Flag locality, Cape Bruce, Mac-Robertson Coast [*Tilley*, 1937b; p. 21]; analyst: C. E. Tilley.

South Shetland Islands. The paper published by *Barth* [1940] is a summary of the one above.

Barth and *Kvalheim* [1944] published optical and spectroscopic data on tridymite from Deception Island, South Shetland Islands.

Bodman [1916] includes petrographical descriptions of 25 rock specimens collected from the Hope Bay area, Louis Philippe Peninsula, and nearby islands. Many of the specimens are erratics. Six granites, ten diorites, mainly quartz diorites, four gabbros, one odinite, three diabases, and a tuff are described.

Broch's [1927] report comprehends microscopical descriptions of basalts, trachyandesites, andesite, and highly decomposed rocks representing dredgings off the west coast of Peter I Island, lying northeast of Thurston Peninsula.

The paper of *Geikie* [1898] includes brief petrographical descriptions of granites and a green tuff collected from a beach on Dundee Island, lying eastward of the tip of Palmer Peninsula.

Gourdon [1905, 1906, 1907, 1908, 1910, 1914abc, 1917] has contributed to our knowledge of the islands lying off the western coast of Palmer Peninsula. The papers written in 1905, 1906, and 1907 are included in the report of 1908. The papers written in 1910 and 1914 are included in the publication of 1917. The monograph of 1908 comprehends descriptions of granites, quartz diorites, and gabbros, as well as rhyolite, trachyandesites, dacites, andesites, labradorites, a diabase, and basalts, all representing a typical West Antarctica assemblage. These specimens were collected principally from islands of the Danco and Graham Coasts. In the report of 1917 a study is made of zeolites from King George Island, South Shetland Islands, and from Jenny Island, off southeast coast of Adelaide Island. Petrographical notes are recorded of igneous rocks from Bridgman, Deception, and King George Islands, South Shetland Islands, Jenny Island and Leonie Islets, off southeast coast of Adelaide Island, and Webb Islet, off east coast of Adelaide Island. In the main, these rocks are extrusives, including trachyandesites, andesites, labradorites, and dolerites.

Holtedahl [1929] records one chemical analysis of a schistose rock from Clarence Island on page 109.

Knowles [1945] includes brief petrographical descriptions in his paper on the geology of southern Palmer Peninsula. The massive intrusives include granite, granodiorite, quartz diorite, nepheline syenite, hornblendite, gabbro, and apatite monzonite. Nepheline syenite is only listed. Reference is made to a small amount of leucite in a biotite granodiorite. Dike rocks include pegmatite, minette, diabase, hypersthene diabase, augite basalt, olivine dolerite, aplite, and enstatite basalt. The extrusives are seen in porphyritic felsite. The metamorphic rocks include gneiss, hornfels, slate, and mica schist. The sedimentary rocks include arkose, graywacke, conglomerate, and mudstone.

Nordenskjöld [1905] divides West Antarctica into 'Die Zone der Gebirgskette,' principally intrusive rocks, and 'Die östliche Zone (Zone der Erguss- und Sedimentgesteine.)' The paper includes petrographical notes on granites, quartz diorites, porphyries, porphyrites, tuffs, and sandstones, which specimens were collected principally from the Hope Bay area, Louis Philippe Peninsula, and islands lying to the east.

Pelikan [1909] records the results of petrographical studies of rocks collected from islands, principally those of the Palmer Archipelago, off the coast of Palmer Peninsula, between latitudes 64°02′ and 65°04′, and from the Danco Coast. The rocks include granite, quartz-augite diorite, augite diorite, granophyre, orthoclase porphyry, diorite porphyrite, gabbro porphyrite, diabase, tuff, andesite, basalt, basanite, and various dike rocks, as aplite and lamprophyre.

Petersen [1895] describes the basalt of Mount Christen Christensen (Christensen-Vulkan), Robertson Island, southward of the Nordenskjöld Coast.

Prior [1898] briefly describes basalts, palagonite tuff, granite, and glauconitic sandstone from Cockburn Island, southeast of Louis Philippe Peninsula.

Stewart [1934a] makes comparisons between the quantitative microscopical and volumetric chemical-mineralogical determinations of 20 specimens from Victoria Land, Marie Byrd Land, George V Coast, and Greater Mackellar Islet, off George V Coast, and West Antarctica. *Stewart* [1934e] briefly compares the igneous rocks of the Queen Maud Range, Victoria Land, and those of Edward VII Peninsula with specimens from West Antarctica. *Stewart* [1937] makes a petrographic study of rocks collected by the Swedish Antarctic Expedition, 1901–1903, from Cockburn, James Ross, Red, Seymour, and Snow Hill Islands, southeast of Louis Philippe Peninsula. *Stewart* [1945a] reports briefly on the igneous rocks, including principally granodiorites and tonalites, from the Melchior Islands, Palmer Archipelago. Comparisons are made with rocks of similar nature collected from Hoseason and Hovgaard Islands, Palmer Archipelago, and Booth Island, Dannebrog Islands group, off Graham Coast. *Stewart* [1947] makes a detailed petrographic study of the igneous rocks of the Melchior Islands, Palmer Archipelago. The rocks vary from alaskite to gabbro.

Thomas [1921] describes the rocks of the Innes Wilson collection from Deception and Roberts Islands, South Shetland Islands, Trinity Island, lying off the northwest coast of Palmer Peninsula, and the Danco Coast bordering De Gerlache Strait. The paper embraces petrographical descriptions of hyaloandesites, tuffs, pyroxene andesites, soda trachytes, and olivine dolerite from Deception Island; olivine basalts, tuffs, and boulders of quartz diorite from Roberts Island; olivine basalts, the prevalent type, from Trinity Island and the Danco Coast.

Tilley [1930] submits brief petrographical descriptions of some metamorphic rocks collected from the southern extremity and from the west coast of Elephant Island, South Shetland Islands.

Tyrrell [1921] treats ably of the petrography of a collection of rocks, principally igneous, from the South Shetland Islands, the Palmer Archipelago, Trinity Island, and the Danco Coast. The intrusive rocks range from granites to olivine gabbros, whereas the extrusive rocks are best represented by bandaites, although some of the lavas have basaltic affinities, and some are subacid and acid in composition. Tuffs, igneous breccias, and altered lavas are described. A few sedimentary rocks are noted in the collection.

Tyrrell's [1945] report on rocks from West Antarctica and the Scotia Arc is, again, extremely well written. One hundred forty-one rock specimens were collected from the South Shetland Islands, of which the majority were retrieved from King George Island. King George Island, and probably all the larger islands of this group, are composed mainly of rhyolites, dacites, andesites, and other extrusives, with their tuffs, volcanic breccias and agglomerates, which are interbedded in places with argillaceous and arenaceous sediments. This series is intersected by a number of tonalite, diorite, and gabbro intrusions. The lavas of Penguin Island (King George Bay, King George Island) and Bridgman Island, South Shetland Islands, are olivine basalts. Olivine basalt was also erupted at Deception Island, but the main products of this volcano are slaggy and glassy andesites. Petrographical data accompany the more generalized rock descriptions. Data are given of rocks collected at Cape Roquemaurel, Louis Philippe Peninsula, including granite, spessartite, and dacite; from Port Lockroy, Wiencke Island, Palmer Archipelago, in the form of tonalite and porphyritic microtonalite; from dredgings off the west coast of Adelaide Island, as seen in granite, granophyre, granodiorite, tonalite, quartz diorite, dioritic lamprophyre, quartz gabbro, rhyolite, dacite (or dellenite), andesite, and andesitic breccias. The petrography of dredged stones from south of Clarence Island, South Shetland Islands, is then treated. These include quartz diorite porphyry, hornblende-quartz porphyry, spherulitic quartz porphyry, rhyolite, greywackes, carbonaceous sericite phyllite, quartzose phyllite, quartz-sericite schist, and calc-sericite schist. Four-fifths of the dredged stones belong to metamorphics. The rocks of the Gibbs Islands group, South Shetland Islands, are schists and serpentine. Dunite-serpentine is apparently reported for the first time from West Antarctica.

Wordie's [1921] contribution embodies a description by Tyrrell of the petrography of the rocks of Elephant Island, South Shetland Islands. These rocks possibly represent very fine muddy andesitic and basaltic tuffs.

Rocks of Marie Byrd Land – Victoria Land and outlying islands—Approximately the same number of papers relating to the petrology of Palmer Peninsula and its outlying islands have been published as have been printed relative to Marie Byrd Land – Victoria Land and outlying islands, although the latter, in the main, are more voluminous. The contributions have been principally by *Benson* [1916], *Cohen* [1916], *Cotton* [1916], *David* and others [1896], *Fenner* [1938], *Jensen* [1916], *Mawson* [1916], *Mountain* [1925], *Passel* [1945], *Prior* [1898, 1902, 1907], *Rastall* and *Priestley* [1921], *Schetelig* [1915], *Skeats* [1916], *Smith* and *Debenham* [1921], *Smith* and *Priestley* [1921], *Smith* [1924, 1954], *Stetson* and *Upson* [1937], *Stewart* [1934abef, 1939, 1941, 1945b], *Thomson* [1916], *Wade* [1937, 1945], *Walkom* [1916], *Warner* [1945], and *Woolnough* [1916]. Note that the principal contributions are those of National Antarctic Expedition, 1901–1904, the British Antarctic Expedition, 1907–1909, and the British Antarctic ('Terra Nova') Expedition of 1910–1913. *Warner's* [1945] paper on the structure and petrography of the Southern Edsel Ford Ranges is outstanding. It is a pity that the Americans have not published more than the bibliography indicates.

Benson [1916] describes the dolerites from the moraines at Cape Royds, Ross Island, from Stranded Moraines, the Ferrar Glacier Valley, and from points visited by the Northern Party. The rocks are composed of basic plagioclase and pyroxene, chiefly monoclinic, with varying amounts of micropegmatitic intergrowth of quartz and feldspar occurring interstitially. In the collection are quartz, quartzless, and other types of dolerites. Enstatite-augite occurs in abundance in the quartz dolerites.

Cohen [1916] describes aegirine-augite crystals from a microsanidinite out of the trachyte from Mount Cis, Ross Island, Ross Archipelago.

Cotton [1916] presents microscopical notes on four rocks, a camptonite and an augite porphyrite from Cape Ross, a granite from Depot Island, and a basic enclosure (mica diorite) in Depot Island granite.

David and others [1896] present a brief picture of specimens from Possession Island, western area of the Ross Sea, and Cape Adare, the northeastern extremity of Victoria Land. The Possession Island specimens are principally basalts. The Cape Adare rocks include trachyte, limburgite, olivine basalt, and mica schist.

Fenner [1938] contributes a chemical and mineralogical study of olivine fourchites collected from Volcano 116, latitude 76°33′ S, longitude 144°45′ W (approximately), Marie Byrd Land.

Jensen [1916] describes a sequence of rocks considered to be differentiates of a magma of the composition of intermediate kenytes. The rocks were collected from Ross Island, Ross Archipelago. Not only are there descriptions of specimens from Mount Erebus proper, but also from Mount Cis, The Skuary, Turk's Head, Cape Barne, Cape Bird, and Crater Hill. The rocks include such types as trachyte (trachyphonolite), kenyte, vitrophyric kenyte, limburgite, olivine and kulaitic basalts, and leucite tephrite.

Mawson's [1916] paper contains descriptions of specimens, chiefly erratics, from the Beardmore Glacier area, the Ferrar Glacier area, and the coastline between latitudes 78° and 75° S, Victoria Land. The rocks include granites, aplitic granite porphyry, diorites, quartz porphyry, kersantite, and arkose.

Mountain [1925] describes two types of potash-oligoclase from Mount Erebus, Ross Island, Ross Archipelago, collected by the Terra Nova Expedition, from leucite kenytes. Their physical properties are compared with the anorthoclases of Mount Kenya and Kilima-njaro, and chemical analyses of the two Erebus types are compared with a chemical analysis of the Kenya anorthoclase.

Passel's [1945] paper relates to the sedimentary rocks of the Southern Edsel Ford Ranges, Marie Byrd Land. He offers a brief description of the mineralogy of the sediments, which are made up of alternating beds of shale and sandstone. Appended are petrographical notes by Warner, who classifies them as quartzites, slates, and gradational types between the two, the latter being the more abundant.

Prior's [1898] contribution embodies brief descriptions of rocks collected by the Ross Expedition during the three voyages southward. Included are data relating to basalts, palagonite tuff, phonolite, and granite from Possession Island, western area of the Ross Sea, and a basalt from Franklin Island, located in the Ross Sea about 80 miles east of Victoria Land. *Prior* [1902] records petrographical descriptions of granites, plagioclase-olivine-augite-biotite rock, quartz felsites, slates, quartz grits, basalts, phonolitic trachytes, and kenytes, collected from areas including Cape Adare (northeastern extremity of Victoria Land) Robertson Bay (northern Victoria Land), Possession Island (western area of the Ross Sea), Franklin Island (80 miles east of Victoria Land), Ross Island (Ross Archipelago), and Coulman Island (west coast of the Ross Sea). *Prior's* [1907] monograph comprises petrographical descriptions of a portion of a suite of some 1000 rock specimens collected from Victoria Land and some of its islands. The specimens are considered under the following headings: namely, volcanic rocks, crystalline limestones, gneisses and granites, lamprophyric and other dike rocks, the Beacon sandstone, and dolerites.

Rastall and *Priestley's* [1921] paper records brief petrographical notes, by Rastall, on the slate-graywacke rocks of Robertson Bay and the sedimentary erratics collected on the Newnes and Murray Glaciers, of northern Victoria Land.

Schetelig's [1915] contribution comprehends brief petrographical descriptions of rocks, principally granites and gneisses, collected by Amundsen at Mount Betty, Victoria Land, and of those, granite, granite pegmatite, amphibolite, and gneiss, collected by Prestrud at Scott Nunataks, King Edward Peninsula.

Skeat's [1916] paper comprises a study involving an examination of some 40 thin sections of erratics obtained from various localities in Victoria Land, and of two limestones collected *in situ*, which contain *Archiocyathinea*. The erratics are breccias, oölitic limestones, limestones, dolomite (?), and marble.

Smith and *Debenham's* [1921] contribution comprehends quite detailed descriptions of crystalline limestones, pyroxene granulites, and crystalline schists collected in the McMurdo Sound region, Victoria Land. The crystalline schists vary considerably in different parts of the region, including garnet-sillimanite, cordierite-garnet, biotite and biotite-hornblende gneisses, biotite amphibolite, and hornblende schist.

Smith and *Priestley* [1921] present an excellent picture of the metamorphic rocks of the Terra Nova Bay region, Victoria Land. The specimens found *in situ* and described microscopically are garnetiferous biotite gneiss and porphyritic biotite-orthoclase gneiss. Of the collection of erratics, including some 770 specimens, almost every one was thin-sectioned. The principal types are biotite gneiss, muscovite-biotite schist, crystalline limestone, para-granulite, and graphic mica schist.

Smith [1924] presents complete petrographical descriptions of specimens collected in the McMurdo Sound and Terra Nova Bay regions, Cape Adare, Robertson Bay, and Beardmore Glacier areas, Victoria Land. The McMurdo Sound rocks include those of biotite granite (hornblende-free granodiorite), which rock type contains numerous inclusions of gneisses, granulites, and limestones, para-pyroxene granulite, aplite, pink hornblendic biotite granite, pegmatite, quartz-orthoclase porphyry, augite-bearing vogesite, camptonite, spessartite, hornblende lamprophyre, augite-biotite kersantite, and biotite porphyrite. Reference is made to the quartz dolerites. The majority of the specimens were collected *in situ*. The Terra Nova Bay rocks were collected from *in situ* occurrences and as erratics. Among those erratics collected from Evans Cove Beach are several types of rocks similar to those described from the McMurdo Sound region. Descriptions of two enstatite peridotite erratics are given. Biotite diorites, collected from outcrops are described in some detail, as well as granites and microgranites found intruding the diorites. Less space is given to hornblendic biotite granite, aplites, and pegmatites. A number of erratics collected at Cape Adare and in the vicinity of Robertson Bay are briefly described. Brief statements are recorded as to the nature of the quartz dolerites and granites obtained in the Beardmore area.

Smith's [1954] monograph "deals with the volcanic rocks collected on Ross Island and also with a few specimens obtained from two of the very rare exposures of volcanic rocks on the mainland opposite Ross Island in the Koettlitz and Ferrar Glacier regions." This work is divided into five parts, namely: (1) the distribution of the volcanic rocks, (2) phonolitic trachytes and trachytoid phonolites, (3) kenytes, (4) basalts, and (5) summary and concluding remarks. The first part provides the background for the detailed petrography, relating to areas of the Ross Archipelago from which collections have been made by various expeditions, and the rock relationships as to ages of the different kinds of lavas. Part 2 treats of the petrography of (1) phonolitic trachyte (Mount Cis type), (2) trachytoid phonolite (Mount Terror type), and (3) trachytoid phonolite (Observation Hill type). Lastly, descriptions are included of phonolitic trachytes not included in the Terra Nova collections. Part 3 relates to the kenytes. Some space is devoted to the use of the name kenyte. According to Smith, *Prior* [1902, p. 329] seems to have been the first to mention kenyte in Antarctica. The kenytes of Mount Kenya differ from those of Mount Erebus in that nephelite is present in the former and absent in the latter. Again, considerable attention is paid to the feldspar insets of the kenytes. Haüyne is reported for the first time from Antarctica. The varieties of kenyte are: (a) with holocrystalline and hemicrystalline groundmass, and (b) with glassy groundmass. In Part 4, the basalts are described. All of the basalts of the Ross Island region which were examined contain small amounts of the feldspathoids in the groundmass. On the basis mainly of their insets and microinsets the basalts are divided into two principal groups, namely: (1) those with conspicuous insets of plagioclase and microinsets of olivine, and (2) those with insets of augite as well as tabular insets of plagioclase and microinsets of olivine and magnetite. The first type is almost restricted to Mount Erebus. Reference is made to the basalts of the mainland opposite Ross Island which resemble rather closely those of the Ross Archipelago.

Stetson and *Upson's* [1937] paper embodies the results of the investigations of the mechanical and mineralogical compositions of twelve cores collected, by the Second Byrd Antarctic Expedition, in the Ross Sea, the majority obtained near the Ross Shelf Ice.

Stewart [1934a] makes comparisons between the quantitative microscopical and volumetric chemical-mineralogical determinations of 20 specimens from Victoria Land, Marie Byrd Land, George V Coast and Greater Mackellar Islet, off George V Coast, and West Antarctica. *Stewart* [1934b] records a quantitative microscopical study of various igneous and metamorphic rocks collected in the Mount Fridtjof Nansen district, Queen Maud Range, Victoria Land. *Stewart* [1934e] briefly compares the igneous rocks of the Queen Maud Range, Victoria Land, and those of Edward VII Peninsula with specimens from West Antarctica. *Stewart* [1934f] makes a quantitative microscopical study of arkoses from Mount Fridtjof Nansen, Victoria Land, collected by the Byrd Antarctic Expedition, 1928–30, and of other specimens of the Beacon formation collected by the National Antarctic and British Antarctic (Terra Nova) Expeditions in the more northerly and westerly parts of Victoria Land. *Stewart* [1939] submits a petrographic quantitative study of the mineral composition of certain intrusive rocks of Victoria Land and compares these rocks with those examined from other areas of the Antarctic. *Stewart* [1941] reports on a petrographical qualitative study of 44 metamorphic and three sedimentary rocks collected in the Edsel Ford Ranges, Marie Byrd Land, and makes comparisons of these rocks and those examined from other Antarctic lands. *Stewart* [1945b] gives a report on a quantitative microscopical study of 33 quartz-bearing and four intermediate intrusive rocks collected in Edward VII Peninsula and Marie Byrd Land by the Second Byrd Antarctic Expedition.

Thomson's [1916] paper relates to the inclusions of the volcanic rocks of the Ross Archipelago. The microscopical descriptions include those of olivine, pyroxene, and gabbroid nodules from the basalts and limburgites of Hut Point; sanidinites, microsanidinites, and plagioclase-pyroxene inclusions in the trachyte of Mount Cis, sandinidinites and microtinites in kenytes from Cape Royds, Inaccessible Island, and Tent Island, and in erratics from Cape Royds and Cape Barne, microsanidinite in a basic rock from Hut Point; erratic sanidinite from Cape Royds; orbicular augite syenite erratic from near Mount Cis; quartz-bearing inclusions in kenyte of Cape Royds and Sentinel Hill, and hornblendic inclusions in trachytes from Observation Hill and Cape Bird. Suggested origins of the sanidinites, microtinites, and hornblendic inclusions, and a classification of them are given.

Wade [1937] reports a brief quantitative petrographical study of igneous rocks composing the mountains of the Edsel Ford Ranges, Marie Byrd Land, as represented by specimens collected by the Eastern Sledge Party, Second Byrd Antarctic Expedition. Reference is made to the metamorphic rocks and an arkose collected in the area. *Wade's* [1945] paper, relating to the geology of the Rockefeller Mountains, Edward VII Peninsula, contains data on the petrography of the rocks, indicating that a leucogranitic type is the principal intrusive in the mountains.

Walkom [1916] submits a report on the pyroxene granulite erratics collected at Cape Royds, Ross Island, Ross Archipelago. Three classes are considered, namely, acid pyroxene granulites, scapolite-bearing pyroxene granulites, and basic pyroxene granulites. Fifteen specimens are analyzed qualitatively with the microscope. Garnet is absent from the series, whereas sphene is a constant constituent, in contrast with the composition of pyroxene granulites from other parts of the world.

Warner's [1945] paper embodies a fine petrographical study of the igneous and metamorphic rocks of the Southern Edsel Ford Ranges, Marie Byrd Land. The plutonic rocks include granodiorite and granite together with intermediate types of monzonitic composition, as well as leuco representatives of all these types. Plagioclase is nearly always zoned. Myrmekitic intergrowths of quartz and feldspar are common. Nearly all the dike rocks are either acid or basic, and the two types are equally abundant. Intermediate varieties are extremely rare. Most of the acid dikes are aplites. Porphyritic dikes with compositions apparently intermediate between aplite and andesite occur sparingly. Of the basic dike types, pyroxene andesite is noted. The metamorphic rocks are represented by biotite and amphibolite schists. The volcanic rocks are of basaltic composition.

Woolnough [1916] relates the microscopical descriptions of erratics collected at Cape Royds, Ross Island, Ross Archipelago. The rocks are pegmatites, aplite, sodalite syenites, quartz diorite, granophyric granite porphyry, granophyre, feldspar porphyry, minettes, vogesite, porphyrite, sericitized diabase porphyry, sölvsbergites, sapphire-bearing trachyte, corundum-bearing trachyte, spherulitic trachyte, dense porphyritic basalt, actinolite gneiss, tremolite gneiss, actinolite schists, fine tremolite schist, spotted schist, phyllite, quartz schist, and micaceous sandstone.

Rocks of George V and Adelie Coasts—The rocks of George V and Adelie Coasts have been made known to us through the Australasian Antarctic Expedition, 1911–1914, under the leadership of Mawson. The geological results are observed in two volumes. The contributors to the petrology of this region are *Bayly* and *Stillwell* [1923], *Berthois* [1935], *Browne* [1923], *Coulson* [1925], *Glastonbury* [1940bcdef], *Kleeman* [1940], *Mawson* [1940abc], *Nockolds* [1940], *Stewart* [1938], *Stillwell* [1918, 1923], *Summers* and *Edwards* [1940], and *Tilley* [1923, 1940a].

Bayly and *Stillwell's* [1923] paper comprehends a description of the only stony meteorite which has been found in the Antarctic. Chemical analyses of the meteorite are listed.

Berthois' [1935] paper is a very brief petrographical analysis of a quartz diorite collected by Dumont d'Urville in 1840.

Browne [1923] discusses the dolerites. The text is divided into two parts, the first dealing with the petrography and chemistry of a portion of a dolerite sill noted in 'King George Land,' and the second with the dolerite erratics collected in 'Adelie Land.' There are included in the petrographical descriptions three quantitative microscopical analyses.

Coulson [1925] submits descriptions of 22 schist and gneiss erratics from Cape Denison, which are characterized by an abundance of either magnetite or garnet or both. These metamorphic rocks have been derived from sediments whose compositions have been modified by igneous emanations. Grubenmann's classification is used, and an additional new group of garnet-magnetite rocks is suggested. A study is made of pleochroic halos and nuclei in biotite in a magnetite-garnet gneiss.

Glastonbury's [1940a] paper comprehends a petrographical study of amphibolites and contained xenoliths from Cape Denison, gneisses and amphibolites from Stillwell Island, and gneisses from Madigan Nunatak. These notes supplement the work of Stillwell (vol. 3, pt. 1). *Glastonbury* [1940b] records brief qualitative microscopical descriptions of erratic felsites, granophyres, porphyries, and entirely recrystallized rocks from the moraines. *Glastonbury* [1940c] discusses the basic igneous rocks and their metamorphic equivalents from Commonwealth Bay. He uses Johannsen's modal classification, and follows closely Harker's treatment of metamorphic rocks in the petrographical studies of the specimens collected from the moraines at Cape Denison. The descriptions are of diorites, basalts, dolerites, and gabbros. The metamorphics include representatives of Harker's series *b*, *c*, *d*, *e*, and *f*. *Glastonbury* [1940d] describes 20 epidotic rocks from the moraines, Commonwealth Bay. These specimens are divided into feldspar-epidote, saussuritized-epidote, epidote, epidote-actinolite-feldspar, hornblende (or biotite)-epidote-feldspar, and epidote rocks, and those showing cataclastic effects. *Glastonbury's* [1940e] paper embodies descriptions of thirty-four marbles and gneisses from the moraines. These rocks are characterized by such minerals as actinolite, diopside, epidote, forsterite, garnet, phlogopite, pyroxene, and tremolite. *Glastonbury* [1940f] submits descriptions of some hybrid gneisses from the moraines, Cape Denison. The 17 gneisses described fall into three types, namely, hornblende-feldspar (augen) gneisses, injection gneisses, and pegmatitic rocks containing ferromagnesian constituents.

Kleeman's [1940] monograph relates to the schists and gneisses from the moraines, Cape Denison. The rocks described have been altered by regional metamorphism. Thirty-seven microscopical descriptions of metamorphosed sedimentary rocks are grouped under the headings of argillaceous rocks, argillaceous rocks altered by the addition of volatiles, semi-calcareous argillaceous rocks, impure arenaceous rocks, and unusual types. The descriptions of the 41 metamorphosed acid igneous rocks are grouped under mylonites and cataclastites, rocks in which crushing has been accompanied or followed by a rise in temperature and consequent regional metamorphism, granite gneisses formed by flowing without crushing, tourmaline-bearing rocks, and gneisses formed by the intrusion of granites during the period of orogenic stress. This is followed by petrographical descriptions of 14 rocks of doubtful origin, including garnet rocks.

Mawson [1940a] describes the sedimentary rocks collected by the Australasian Antarctic Expedition under two headings: those collected *in situ*, and those found only as erratics. The only *in situ* occurrence of sedimentary rock noted by the expedition is at Horn Bluff, George V Coast. The series is typified by sandstones that carry coal greatly altered by heat from a dolerite sill intrusion. Cassiterite is recorded as occurring in the *in situ* sandstone. Brief descriptions of nine *in situ* rocks are presented. Forty-one rocks, found only as erratics, are described, some descriptions being microscopic and some megascopic. *Mawson* [1940b] presents a listing and descriptions of the minerals encountered by his expedition. Copious references are made to the descriptions recorded in other parts of volumes 3 and 4 of the expedition reports. *Mawson's* [1940c] paper relates to a catalogue of rocks and minerals collected in Antarctic lands by the Australasian Antarctic Expedition. Close to 1500 rock and mineral specimens were collected by the expedition, of which the greater number are erratics and which do not include the dredgings and the large collections from Macquarie Island. In this paper the individual specimens are listed as to number, descriptive title, locality, and where cited in volumes 3 and 4 of the expedition reports. It would be very useful if future expeditions would follow Mawson's example.

Nockolds' [1940] monograph is divided into two sections: the first, a report on rocks from eastern Queen Mary Coast; the second, a report on rocks from western Queen Mary and Wilhelm II Coasts. Comparisons are made between the rocks of eastern Queen Mary Coast and Wilhelm II Coast, Adelie Land, and Victoria Land. From Victoria Land westward to Wilhelm II Coast the acid rocks "start with predominant granodiorite types and end with alkali granites. A feature of this province, if province it can be called, is the universal presence of orthite in all the acid rocks." Comparisons are made in section 2 between the rocks of western Queen Mary, eastern Queen Mary, and Wilhelm II Coasts. There is a much greater resemblance between the basement rocks of western Queen Mary and Wilhelm II Coasts than between eastern and western Queen Mary Coast. The rocks studied cover granites, pegmatites, quartz and quartz-tourmaline rocks, tonalites, trondhjemitic types, charnockites (acid and basic), other hypersthene-bearing rocks, leucite basalt, metamorphosed igneous and sedimentary rocks, and pseudotachylyte.

Stewart [1938] records brief petrographical descriptions of 11 metamorphic rocks, collected by the Australasian Antarctic Expedition, from Adelie Land.

Stillwell's [1918] monograph, of 230 pages, relates to the petrography and chemistry of metamorphic rocks collected *in situ* at Capes Denison, Hunter, and Gray, Cape-Pigeon Rocks, Greater Mackellar Islet, Stillwell Island, Point Garnet, Madigan Nunatak, and Aurora Peak, collected by the Australasian Antarctic Expedition. The chief rock types include phyllite, gneisses, and amphibolites. Seventy-one specimens are referred to in the text. The nomenclature generally adopted is that of Grubenmann. *Stillwell* [1923] discusses the amphibolites and related rocks from the moraines, Cape Denison. Although complete chemical analyses are not available, the rocks described in this paper are fitted into Grubenmann's classification, inasmuch as the chemical composition is reflected in the mineral composition. The specimens included in the descriptions are amphibolites, gabbro schists and gneisses, magnesium silicate gneisses, and plagioclase gneisses.

Summers and *Edwards* [1940] have written an excellent paper embodying a study of 17 acid igneous erratics from Cape Denison and of five specimens collected *in situ* at Penguin Point.

Tilley [1923] describes a collection of metamorphic limestones representing erratics taken from the moraines at Cape Denison. They include the following types of marbles: forsterite, tremolite, diopside-tremolite, pyroxene-garnet, pyroxene-epidote, and epidote, as well as carbonate-free calc-silicate rocks. *Tilley's* [1940a] paper embodies the description of 29 erratics from the moraines at Cape Denison, including paragneisses, garnet gneiss, sillimanite pegmatite, and cordierite pegmatites, the last composing the majority of the rocks.

Rocks of Queen Mary, Wilhelm II, Ingrid Christensen, Mac-Robertson, and Kemp Coasts, and Enderby Land—Those who have contributed to our knowledge of this portion of the Antarctic are *Broch* [1946], *Mawson* [1940bc], *Nockolds* [1940], *Reinisch* [1906, 1912], *Tilley* [1936, 1937ab], 1940b], and *Zirkel* and *Reinisch* [1905]. In that section devoted to the rocks of George V and Adelie Coasts reference has already been made to the works of Mawson and Nockolds.

Broch [1946] treats briefly of the petrography of rocks collected from Ingrid Christensen Coast. Apparently the rocks are erratics as "some of the samples are roughly rounded, others show no sign of transportation." The specimens described include gabbro, uralite gabbro, biotite-augite tonalite, uralite tonalite, biotite-augite tonalite with hypersthene, biotite-hypersthene tonalite, and biotite-hypersthene tonalite with amphibole.

Reinisch's [1906] monograph contains petrographical descriptions of leucite basalts, 'magmatische Ausscheidungen,' foreign inclusions, and leucite basalt tuffs, collected from Mount Gauss, Wilhelm II Coast. *Reinisch* [1912] makes a study of erratics collected from icebergs in the vicinity of the winter quarters and the moraines of Mount Gauss. The specimens include granite, gabbro, paragneisses, carrying garnet, sillimanite, and cordierite, orthogneisses, amphibolite, crystalline limestone, quartzite, sandstone, and leucite basalt tuff.

Tilley [1936] suggests the name enderbite for an acid member of the charnockite series characterized by rhombic pyroxene in which the plagioclase (oligoclase or andesine) is the essential feldspar. Enderbite is noted in the group of rocks collected by the BANZ Antarctic Research Expedition, 1929–1931. *Tilley* [1937a] makes a petrographical study of rocks collected *in situ* and as erratics from Proclamation Island, Enderby Land. Rocks of the charnockite series probably represent the principal rock types of the island, and are classified as ultrabasic, basic, and acid. Included in the descriptions are microscopical data on garnet orthogranulites, which specimens were collected principally from *in situ* exposures. There are also petrographical descriptions of erratics with no clear relationship to rock types met with *in situ*, including gneisses of igneous and sedimentary origin and metamorphosed dolerites. *Tilley* [1937b] describes a collection of rocks from Mac-Robertson Coast. Some 50 specimens represent the collections at Scullin Monolith and Cape Bruce. The rocks are all coarse-grained and the most outstanding feature is the prevalence of red garnet. About one-quarter of the rocks examined are paragneisses, the remainder being igneous or contaminated rocks. *Tilley* [1940] reports briefly on rocks collected from Scullin Monolith, Mac-Robertson Coast, and those from Bertha Island, off Kemp Land. The Scullin Monolith specimens are represented dominately by a coarse-grained quartz-microperthite gneiss, with garnet and biotite as the chief ferromagnesian constituents. Hornblende norite is briefly described. The rocks collected from Bertha Island include a garnet-hornblende-microperthite-quartz gneiss, the dominant type, a microperthite-quartz gneiss, a quartz-plagioclase (andesine)-garnet gneiss, hypersthenite, garnetiferous hypersthenite, mangerite passing into quartz norite, and a group of basic rocks which may be described as metamorphosed gabbros or norites.

Zirkel and *Reinisch* [1905] describe specimens of rocks collected by dredging operations of the Valdivia Expedition some 100 miles north of Enderby Land. Listed rocks include biotite granite, hornblende granite, aplite, quartz-hornblende porphyries, diabase, various gneisses, including sillimanite and cordierite, amphibolite, biotite and sillimanite-biotite schists, sandstone, graywacke, and phyllite.

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Some Problems of Antarctic Submarine Geology*

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Abstract—The available information about submarine geology in the Antarctic region is briefly surveyed. Suggestions for observations to be made during the International Geophysical Year are offered, particularly in relation to Pleistocene climactic changes.

Introduction—This paper has been prepared as a discussion of the investigations which the authors would be interested in making if they were working in the Antarctic area. It is presented in the hope that it may be of use to some who go to Antarctica in connection with the International Geophysical Year program. The effort is made to explain the purposes of the various proposed investigations, to outline relevant observations which might be made during travel to and from Antarctica, and to indicate areas of particular interest.

An excellent summary of the present knowledge of the geology of Antarctica has been given in the preceding papers. As pointed out by *Tyrell* [1945] and by *Fairbridge* [1952], the rocks of the islands adjacent to Graham Land are like those of the Patagonian Andes, while the lavas of the South Sandwich islands show greater affinity with comparable rocks of the West Indies.

All other islands in the Antarctic region are apparently built up of rocks belonging to the olivine basalt-trachyte association following the simple pattern characteristic of mid-ocean islands. The predominating lavas are olivine basalts, usually more alkaline and less siliceous than continental floor basalts. References are given to accounts of the petrology of almost all of these islands.

The continental shelf—High on any list of problems of submarine geology for the Antarctic area is as detailed an investigation as possible of the continental shelf and slope. The fact that the shelf is generally considerably deeper than in other parts of the world has been the subject of many remarks. A depth of two to three hundred fathoms is commonly found before the break in slope which marks the edge of the continental shelf, indicated by a dotted line in Figure 1. This is similar to the shelf found along parts of the coast of Greenland, and the hypothesis has been offered that it measures the depression caused by the weight of the ice cap. If this is true, a very slow rate of sedimentation during Pleistocene is implied. Hence, it is possible that piston core samples taken on the shelf might reach sediments older than those usually sampled on continental shelves by this method.

A second possible cause of the lowered shelf is given by *Shepard* [1948, p. 141] where it is implied that the shelves of Greenland and Antarctica have been cut down by glaciers. In either case, it appears that piston core samplers would have an excellent chance of reaching older sediments, and of determining the true cause of the abnormal depth of the continental shelf of Antarctica.

Seismic refraction profiles would be desirable, across the continental shelf, in order to measure the total thickness of unconsolidated and semi-consolidated sediments deposited at the margin of this continent, and compare it with that at other continental margins of the world. Many writers hold that the eastern part of the Antarctic continent is a crystalline shield, while the western part is considered to be folded cordillera of the circum-Pacific belt. It is desirable to compare the total accumulation of continental-shelf sediments in these two areas, where geographical factors are so similar, and the tectonic factors supposedly so different. Seismic profiles of sufficient length to reach basement rocks should also be made in the Ross Sea and Weddell Sea areas to determine the structures of these embayments, and to begin investigation of a possible sea connection between the two.

Photography of the bottom on the shelf and slope would be of particular interest for comparison of the occurrence of ocean-bottom ripple marks on the margins of this Continent with that in other areas of the world. The origin of ripple marks below the accepted depth of wave action in ocean areas in general is not yet understood. The relative importance of astronomic tides, storm surges, tsunamis, turbidity currents, microseisms, and of the main circulation is not yet known. Conditions here differ so radically from those found elsewhere, that we may hope to find in Antarctic waters definitive evidence for conclusions about the relative importance of several

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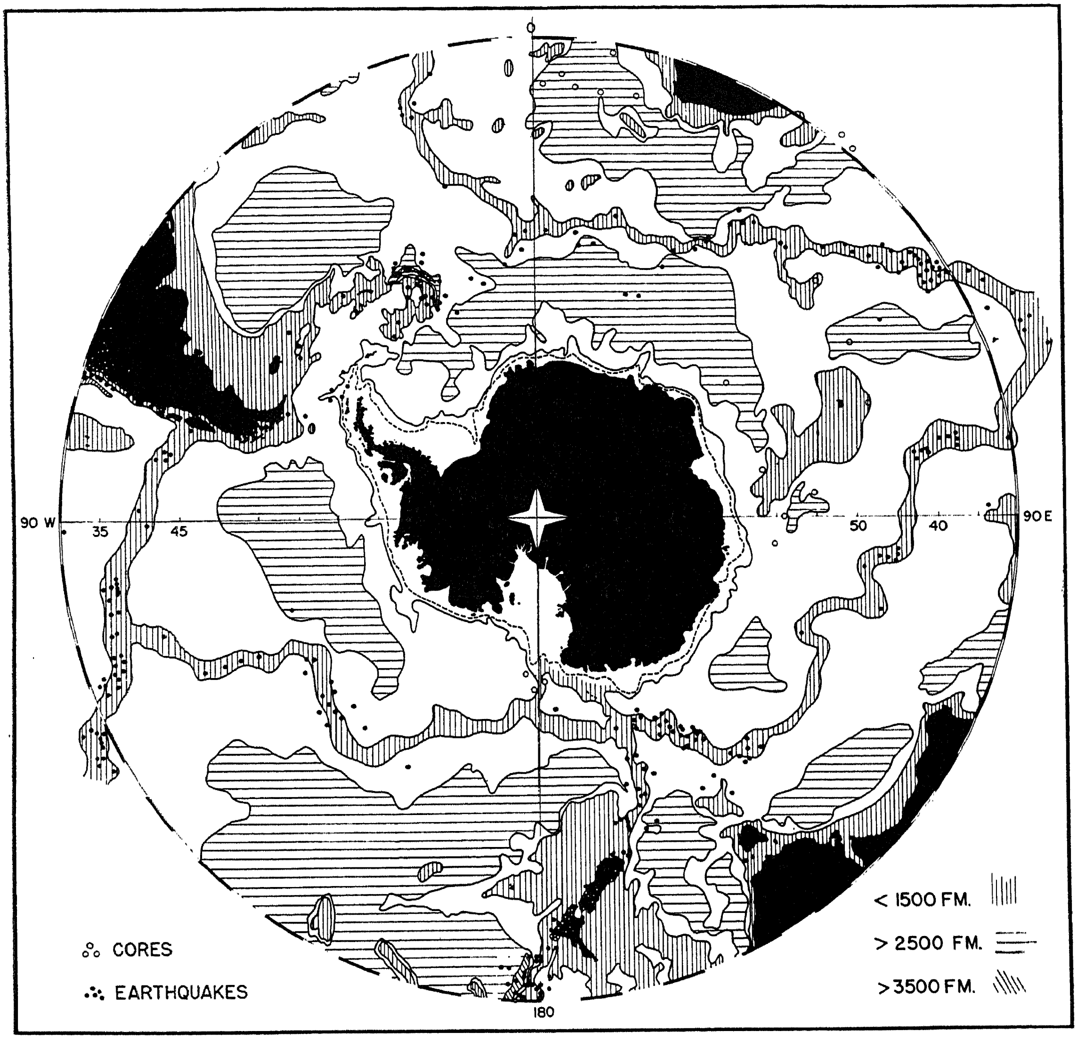

FIG. 1 – Major topographic features of Antarctic Seas; the continental margins and the crests of the major oceanic ridges, areas of less than 1500 fathoms, are shown by vertical shading; the major basins, areas deeper than 2500 fathoms, are shown by horizontal shading; the South Sandwich, Tonga, and South American trenches, areas of greater than 3500 fathoms, are shown by diagonal shading; earthquakes, indicated by solid dots, include all listed by *Gutenberg* and *Richter* [1954] and all reported by the U. S. Coast and Geodetic Survey through April, 1956; all sediment cores long enough to reveal stratification are indicated by open circles; this includes virtually all cores ever taken in the area, with the exception of some cores taken by the *Meteor* in the South Atlantic and those taken by the *Bear* off the Ross Shelf

of these factors in ocean bottom ripple formation. The ripples are probably the key to understanding the motion of the water that is in contact with the ocean bottom.

The existence and character of submarine canyons in high latitudes is a question of considerable importance. Thanks to the excellent work of *Discovery* [*Herdman*, 1948], numerous lines of soundings are available which indicate rough topography in areas of the continental slope and rise where submarine canyons might be expected. There is need for a detailed study of several canyons in the Antarctic area, the study to include zig-zag tracks of echo sounding which cross the canyons repeatedly, and for sediment samples from the floors, the walls, and the undisturbed areas adjacent to the canyons. These are needed to establish the existence of the canyons and to give some indication of the most recent time at which these canyons were being swept clear of sediments. If the canyons exist, we judge from experiences in canyons in moderate latitudes, that Tertiary or older sediments could be sampled from their walls. Such samples could give climatic indications to supplement the opinions reached by the study of fossils from the continent itself. It seems probable that a more complete climatic record could be obtained from submarine sediments than from continental samples.

Raised beaches have been reported as conspicuous features of coastal topography in a number of locations in the Antarctic area. A systematic search for submerged terraces should be made.

Problems of the basins—If submarine canyons are found, it will be desirable to see if they extend to the floors of the basins (see Fig. 1) as they do in lower latitudes, and if the floors of these basins are abyssal plains. Contrasts in sediment type are to be expected between sediments from the abyssal plain and sediments from the inter-canyon continental rise areas. These should make it possible to establish the record of pelagic sedimentation here as has been done farther north. Available soundings are scarce and most of them lack the precision required for proper abyssal plain studies. But even so, they indicate the strong probability that major abyssal plains adjacent to the Antarctic Continent will be found near longitudes of 120°E, 30°E, 20°E, 20°W, and 110°W (see Fig. 1). Long piston core samples taken from suitable topographic locations in these basins will give definite information about climatic changes well back into the Pleistocene and possibly considerably farther.

If precision depth recorders are available, the slopes of the abyssal plains should be measured with care, for these indicate the direction of transport of sediment, hence, in most cases, the sources of the sediments which are building the floors of the abyssal plains.

It would be well worth making a search to find several sea knolls rising gently above the floors of any abyssal plains which may be discovered, and to take long piston core samples of the sediment on the knolls and on the adjacent plain. It has been shown in earlier studies that this type of sampling identifies and clearly separates the pelagic sediments from those of turbidity current deposits. A record of surface ocean water temperatures can be read from the pelagic sediments from the knolls, and an estimate of the changing rate of deposition of terrigenous sediments can be made from the samples on the abyssal plain.

Closely spaced profiles of temperature and salinity of the water as functions of the depth, and extending entirely to the bottom are needed in each of the basins together with large water samples for radio-carbon age determinations. These are needed for determination of deep water circulation rates and patterns, sill depths between adjacent basins, and for the consideration of any sediment temperature profiles which may be obtained in the basins.

Deep-sea stratigraphy—The present conception of the stratigraphy of deep-sea sediments in the Antarctic region is that the continent is surrounded by a zone of glacial marine sediment, typically unsorted terrigenous material ranging from clay to boulders, which varies in width from about 200 to about 700 miles. Beyond this is a zone of diatom ooze, which is slightly wider. Northward of the limit of the diatom ooze, the typical pattern of deep sea sedimentation is found; that is, there is globigerina ooze in the lesser depths and red clay in the greater ones. These conclusions, however, have been based primarily on samples which represented only the first few centimeters of the bottom. A few of the more recent ones penetrate two meters.

The glacial marine sediments are interpreted as marking the area which receives ice rafted continental material. The abundance of diatoms is usually understood to be associated with the upwelling of the deeper water south of the Antarctic convergence, while the red clay and globigerina ooze areas are taken as characteristic of the sedimentation beneath a well-developed, stable thermocline. A northward or southward migration of any of these oceanographic boundaries would be recorded by a gradual thinning or thickening of the corresponding sedimentary bed. Indeed, *Schott* [1939] has recorded this phenomenon as occurring in the southern Indian Ocean. It is certain that a sampling of these sediments, with the longest possible cores taken with piston coring apparatus at core locations properly chosen with respect to the local topography, can give a clear-cut record of any major changes in the position of the Antarctic convergence and any attendant changes in the oceanic temperatures or circulation. It is reasonable to expect that the cores can give the climatic history through the greater part of the Pleistocene, and possibly well beyond that.

These deep-sea sediments should record clearly any changes from a glaciated to an unglaciated condition of the Antarctic continent which have occurred. They may also be expected to indicate the rate of production of the cold bottom water which at present spreads into the Atlantic, Pacific, and Indian Oceans. As is well known, these waters are very corrosive and tend to prevent the deposition of calcareous fossils in the sediments which they contact. Knowledge of the changes in circulation of these waters may help to explain the present riddle about the contrast in sedimentary types between East Equatorial Pacific cores and Equatorial Atlantic cores.

Murray and *Philippi* [1908] found sands in the Cape Basin between South Africa and the continuation of the Mid-Atlantic ridge west of Walvis Bay, and in the Romanche Trench. This was the first mention of deep-sea sands, which led Murray and Philippi, and later *Andrea* [1922] to conclude that these areas represented recently subsided continental blocks. These ideas persisted until recent studies of bottom topography and of numerous long sediment cores proved that sands could be carried hundreds of miles seaward, and deposited in graded, well sorted beds, by turbidity currents.

Studies to demonstrate the turbidity current origin of the first deep-sea sands ever reported could be made from the vessels which will visit Antarctica during the IGY. Two lines of evidence are available, direct examination of sediment samples and delineation of abyssal plains by precise echo soundings. The basins adjacent to Antarctica need investigation even more than those slightly farther north.

It is possible to make some inferences about all the rock types represented in the Antarctic continent by sampling and analyzing erratics available on land, or on those which have been carried to sea by ice so recently that they may be collected by dredging on the ocean floor. Probably there were once rivers on the Antarctic Continent, but most or all of the evidence of these on land is now obscured. On the outer parts of the continental shelves, on the continental slopes and the continental rises, it seems certain that evidence of any rivers that existed will be preserved in the form of submarine canyons. These rivers would have sampled the rocks of the Antarctic Continent in a completely different way than the glaciers sample them. Hence, the river-derived sediments which may be picked up in the floors of submarine canyons, in the abyssal plains, and even on the outer parts of the continental shelves can give an entirely new picture of the make-up of the Antarctic Continent.

Oceanic ridges—The Mid-Atlantic Ridge is a well-known feature of the Earth's surface. It runs almost the full length of the North and South Atlantic Oceans and continues around the tip of Africa into the Indian Ocean [*Ewing* and *Heezen*, in press]. After entering the Indian Ocean, this ridge curves through Prince Edward Island and Rodriguez Island to the Gulf of Aden. In the vicinity of Rodriguez Island, the ridge connects with a similar one which may be traced from the vicinity of the Galapagos Islands past Easter Island, across the Pacific, and through the ocean area between the Antarctic continent and the continental platforms of Australia and New Zealand. Of course, the topographic information is sadly incomplete along a large part of the length of these ridges, and a strict contouring of the available soundings can leave many discontinuities in the ridge. However, the belt of earthquakes has been shown to be an accurate marker of the Mid-Atlantic Ridge. The magnificent studies on seismicity by *Gutenberg* and *Richter* [1954] can be used to supplement the bathymetric data in a powerful manner (Fig. 2), and it is on the combination of these two types of information that the continuity of these ridges, as shown in Figure 1, is inferred.

Profiles of the Mid-Atlantic Ridge given by *Stocks* [1933] and *Hill* [1954] and of the Carlsberg Ridge by *Wiseman* and *Sewell* [1937] show that these are characterized by a median rift zone which follows the crest of the ridge very accurately. The rifts frequently show depths much greater than any which can be found within several hundred miles on either side of the ridge's axis. Wherever possible, well-recorded echo sounder tracks across these ridges (Fig. 1) should be provided during cruises arranged for the IGY. Particular areas where the soundings are most badly needed are 50°S, 30°E; 30°S, 50°E; 50°S, 115°E; 55°S, 150–170°E; 55°S, 130°W; from 10°S–10°N at about 100–110°W.

Although the most recent bathymetric charts (U. S. Hydrographic Office no. 2562, and International Hydrographic Bureau no. A′ II) give no indication of such a ridge, there is strong indication in the earthquake epicenters of a connection between Easter Island and the southern part of South America. It would be particularly important to have sounding tracks which would confirm or deny this possibility.

Additional studies of these ridges may be made from oceanographic observations, which can be used for determining the sill depth across a ridge of this sort in many cases. It is particularly desirable to have good deep temperature and salinity observations, extending to bottom, on both sides of the ridge in the areas mentioned above.

There are ridges of a second type which extend into the ocean basins. These are not characterized by seismic activity. A primary example of this type is the Walvis Ridge. Other examples are the Rio Grande Ridge, the Kerguelen-Gaussberg Ridge, the Mascerene or Seychelles Ridge. Classification of the Chagos Ridge is at present somewhat uncertain. The recently discovered Lomonosov Ridge [*U.S.S.R.*, 1954] in the Arctic Ocean, is also

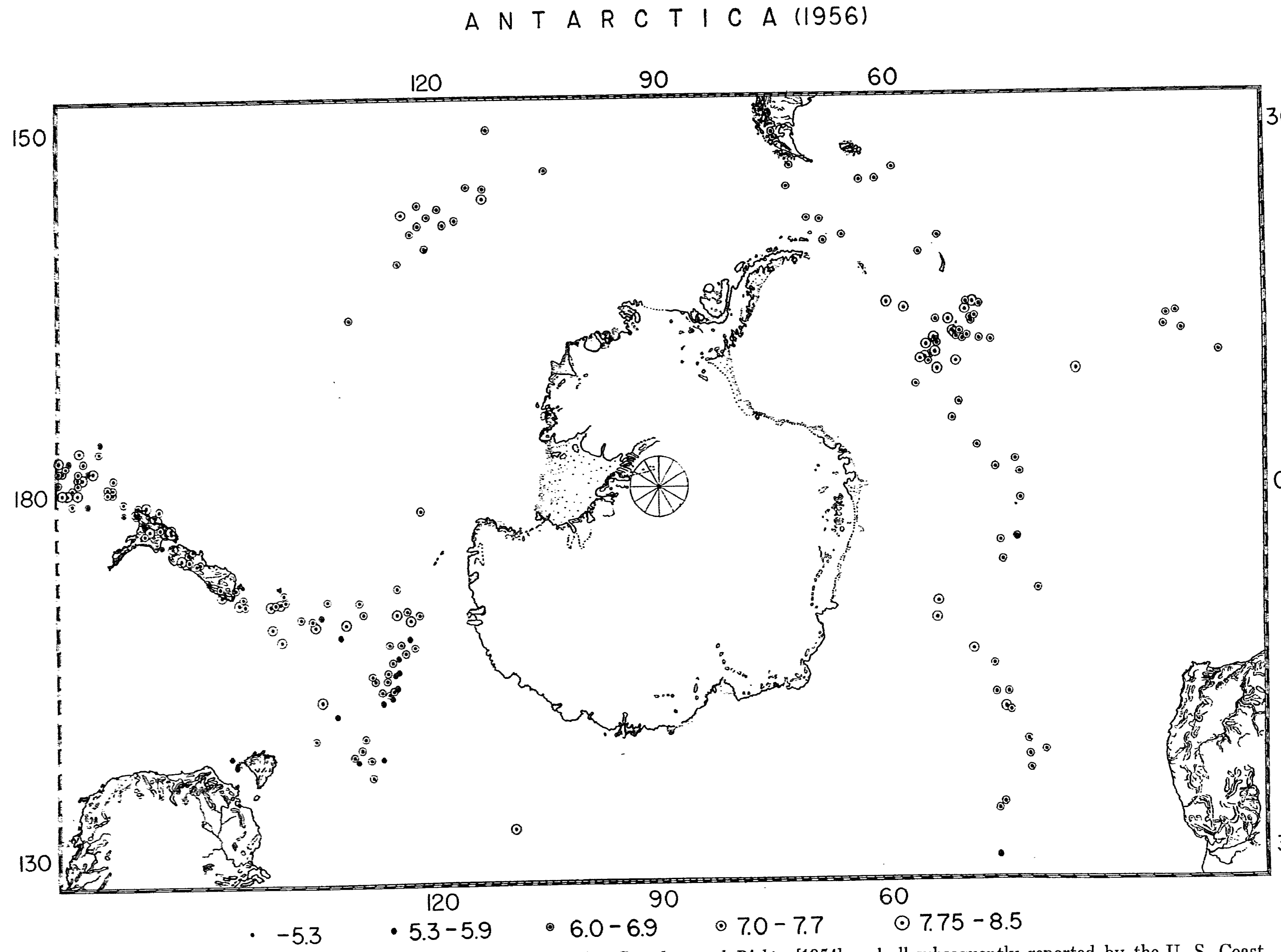

FIG. 2 – Earthquakes of Antarctic area; all earthquakes listed by *Gutenberg* and *Richter* [1954] and all subsequently reported by the U. S. Coast and Geodetic Survey, are shown

aseismic. It is definitely separate from the continuation through the Arctic Ocean of the Mid-Atlantic Ridge earthquake belt [*Raiko* and *Linden*, 1935, *Ewing* and *Heezen*, in press].

Oceanic ridges of the Mid-Atlantic Ridge type are believed to be continuous over great lengths. They apparently have the median rift zone as a characteristic feature throughout, and this rift zone is the locus of the shallow focus earthquakes. The ridges may be traced through poorly sounded areas by the aid of an epicenter map. It must be borne in mind that the rift zone may be the primary feature in this combination and the ridge simply a consequence of the rift. With this viewpoint, it is possible to consider extensions of the rift zone and the accompanying earthquakes from an ocean basin into a continental area such as the East African rift zone, or into an area like the rift zone in the south island of New Zealand.

Seismic refraction measurements at several places on the Mid-Atlantic Ridge have given a velocity of about 7.2 km per second and a thickness of this type of rock too great to penetrate by the seismic measurements [*Ewing* and *Ewing*, unpublished]. This has been interpreted to mean that the ridge is formed by a physical mixture of basalt and dunite from the upper mantle, the effective velocity of sound in the mixture being intermediate between the velocities for the two constituents. A somewhat similar process has been depicted by *Hess* [1954], but it apparently fails to account for the rift valleys and the close association of the earthquakes with them. The extinct submarine volcanoes which are present on the flanks of the Mid-Atlantic Ridge in great numbers, are definitely outside the earthquake belt. This fact emphasizes the point that the earthquakes are too intense to be associated directly with volcanism. These are tectonic earthquakes, almost certainly resulting from continued movement on the faults of the rift.

A third type of oceanic ridge, present in the Antarctic region, is represented by the Scotia Arc (Fig. 1). Whereas all of the rocks extruded on the two types of ridges previously mentioned are oceanic basalts of the Atlantic suite, the igneous rocks of the Scotia Arc are andesitic and granitic, of the Pacific suite of extrusive rocks, together with a metamorphic series. This arc is characterized by a foredeep on the convex side and by an associated earthquake belt, probably much more like the West Indian Arc and perhaps the East Indian Arc than to to the other Pacific island arcs.

It is desirable to have seismic refraction measurements along this arc and particularly in the Scotia Sea to determine whether or not the basement rocks here are similar to those found in the Caribbean, where the greatest velocity reached was 7.2 to 7.4 km per second [*Officer* and others, 1955; *Sutton* and *Ewing*, unpublished; *Ewing* and others, 1955].

Earthquake seismograph installations which are planned for the Antarctic continent during the IGY should make an important contribution to the investigation of the seismicity of this type of arc as well as to that of ridges of the rift type.

Additional topographic surveys in the general area of the Macquarie Islands are badly needed. The rocks of this island are definitely the Atlantic type and appear to be associated with a rift system rather than with a continuation of the circum-Pacific fold belt, as was often suggested by earlier writers. It is true that the earthquake belt following the Easter Island ridge and the Indian-Antarctic ridge in this area branches off and joins New Zealand. It seems likely that the so-called Macquarie swell extending from Tasmania in the direction of Macquarie Island is aseismic and is a ridge of the second (Walvis) type.

Gravity observations offer one of the most powerful means for distinguishing between the rift type ridges and the folded type, as illustrated for instance by studies of the West Indian island arc [*Worzel* and *Shurbet*, 1955] and the Mid-Atlantic Ridge [*Vening Meinesz*, 1948]. In addition to a much-needed investigation of the area around the Scotia Sea by gravity measurements, it would be highly advisable to study the area between the Ross Sea and the Kermadec trench. In former years it was often suggested that the circum-Pacific fold belt continued through from the Kermadec trench, through Western Antarctica, Palmer Land, and the Scotia Arc, into South America. The absence of strong negative gravity anomaly strips between New Zealand and West Antarctica would refute the former interpretation.

It also would be desirable to have gravity profiles, with close spacing of stations, across the rift type of oceanic ridge, and across the Walfish Ridge type of oceanic ridge.

Magnetic investigations of the three types of oceanic ridges are very desirable. Certain progress has been made in the study of the West Indian Island arc and the Mid-Atlantic Ridge. Extension of these to the Antarctic region can be expected to give very useful results.

Comparisons of the South Sandwich trench with the Puerto Rico trench by means of seismic refractions, magnetic, gravitational, and topographic surveys are very desirable.

Seamounts—There is an exceptional opportunity for the study of seamounts in the Antarctic region, where even the small amount of sounding which has been done to date has revealed a great variety of seamounts of various sizes. Many of them are apparently flat-topped, with a variety of depths ranging from approximately 100 to 200 fathoms like the seamounts of the eastern North Atlantic, and from 600 to 800 fathoms like the guyots of the Pacific. It is important to find which of these have flat tops and the depths of the tops. It is important to dredge for rocks and fossils from these mountains in order to establish the date of submergence. Magnetic surveys of a number of these mountains, similar to that which has been made on Caryn peak [*Miller* and *Ewing*, 1956], would be most useful for the study of the question of the reversal of the main magnetic field of the Earth. If sufficient dredge samples are obtained, it is probable that studies similar to those made by *Hamilton* [1956] can give comparisons of the climatic conditions prevailing here with those which prevailed on the mountains in the central Pacific. Pillow lavas recovered from some seamounts from Macquarie Island and from Oamaiu, New Zealand, have shown inclusions of foraminiferal ooze [*Mawson*, 1943], which in New Zealand was of Miocene age. This kind of evidence bearing on the mode of formation of seamounts has been sought in the studies of several of the North Atlantic seamounts without success. Detailed investigations of such occurrences would perhaps settle the question about the growth of seamounts and indicate whether a search for really old sediment uplifted during the growth of seamounts is likely to prove fruitful.

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Geomagnetic Disturbances

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Abstract—The facts and theories of geomagnetic storms and the three great overhead currents of geomagnetic disturbance inferred from surface observations are described. The experimental program of magnetic observations during the International Geophysical Year designed to determine the location and distribution of the inferred overhead currents is explained.

The period of the International Geophysical Year from July 1957 through December 1958 will be a time of maximum solar activity. Sunspots and solar flares, which were practically absent during the past few years, are now beginning to reappear, and in another year or two should be at the maximum of their eleven year cycle of activity. Certain geophysical phenomena, such as geomagnetic disturbances, storms in the ionosphere, auroral displays, and cosmic-ray fluctuations are known to be caused by, or related to, solar activity. It is these phenomena of a stormy or fluctuating character which will be the object of world-wide investigation during the IGY. Indeed, the time of the IGY was purposely chosen to coincide with the maximum of solar activity in order that the relations between the solar eruptions and the terrestrial disturbances may be studied more completely than ever before.

There will be more than 70 solar stations, most of them astronomical observatories, so disposed over the Earth that the Sun will be under continuous observation. In fact, only an unheard-of spread of cloudy weather, or an unprecedented cataclysm, will prevent the Sun from being under observation every instant of the time throughout the IGY. Sunspots will be recorded with telescopes, and solar flares with H_α filters or spectrographs. Solar flares are of special interest. These are bright bursts of red hydrogen H_α light emitted from small areas usually in the region of active sunspots. The number of flares varies roughly linearly with the sunspot number, and in periods of great solar activity there may be as many as ten flares in 24 hours. A flare usually lasts only a few minutes, as far as can be seen from the Earth, but the terrestrial effects which it produces on geomagnetism, the ionosphere and auroral displays may last many hours.

Magnetic disturbances are complex and erratic, with many local differences from place to place. The larger disturbances have certain well-defined characteristics; they are world-wide and often commence suddenly, simultaneously within a minute, at all points over the Earth. The sudden commencement consists in an increase of the horizontal component of the Earth's magnetic field. This is called the 'first phase' of the magnetic storm. It lasts a few minutes or an hour and is then usually followed by a large decrease of the horizontal component, so that it remains below normal for several hours or days. This is called the 'second' or 'main,' phase of the storm. Strong polar disturbances, and usually aurorae, occur during this phase. Finally, there is a period of recovery of a day or more in which the field returns to normal.

World-wide analysis shows that the first phase is such as would be caused by an eastward electrical current flowing in the upper atmosphere around the equator, and that the main phase is such as would be caused by three great electrical currents, measured in hundreds of thousands of amperes, flowing in the upper atmosphere. One of the currents flows in the zone of maximum auroral frequency around the north magnetic pole and across the polar cap, as shown in Figure 1 for the magnetic storm of May 1, 1933 [*Vestine* and others, 1947]. Another current flows similarly in the southern auroral zone across the southern polar cap, and the third current flows westward around the Earth in a broad zone over the magnetic equator. The equatorial current appears to have a belt of greatly increased intensity concentrated in a narrow width of only about 200 km.

It must be emphasized that these electrical currents are merely inferred from the magnetic fluctuations observed on the surface of the Earth. The currents are not known to exist, because the magnetic effects could be caused equally well by magnets or by motions of clouds of diamagnetic or paramagnetic gases, or by combinations of these with various types of currents.

The fact that the geomagnetic disturbances increase and decrease with sunspots is considered to be adequate proof, and indeed at present the only proof, that they are due to bursts of radiation of some sort from the Sun. Neither the type of radiation nor the manner in which it causes the

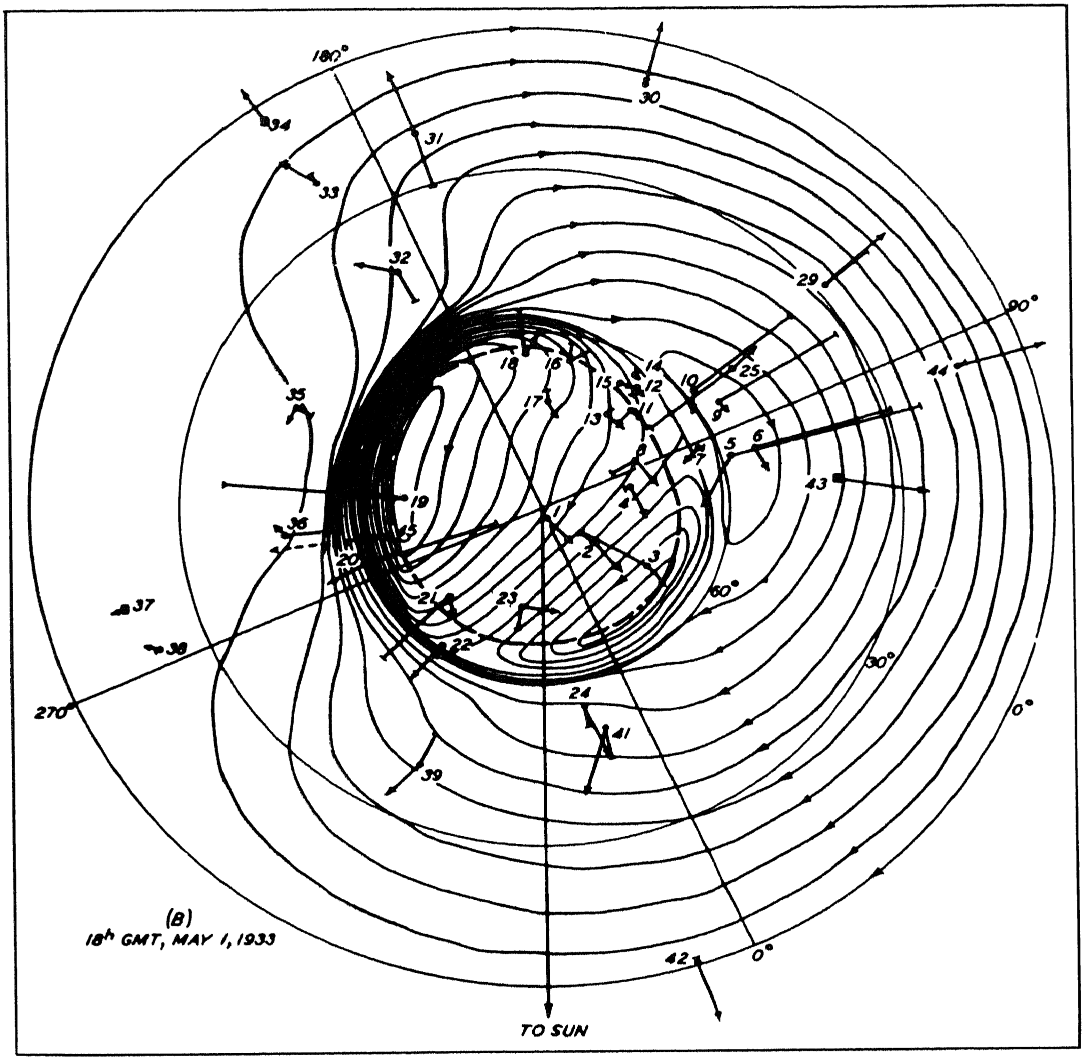

Fig. 1 – Arctic region overhead electric currents inferred from the magnetic storm of May 1, 1933

geomagnetic storms is known. Ultraviolet light and various types of charged particles have been suggested and several theories of their terrestrial effects have been proposed. Each of the theories probably contains elements of correct explanation, but a completely satisfactory theory is not available at the present time.

In their ultraviolet light theory *Maris* and *Hulburt* [1929] assumed that the solar emission was a pulse of ultraviolet light which was absorbed in the upper atmosphere and produced there ionization and winds. These caused electrical currents in the ionosphere which in turn caused the magnetic storm. Their arguments about winds and electrical currents seem sound and in agreement with certain observed ionospheric disturbances which accompany magnetic storms. But their hypotheses to explain the magnetic storm effects in polar latitudes and the aurorae do not now seem adequate. The neutral cloud theory of *Chapman* and *Ferraro* [1933], which is mainly of historical interest, assumed that the solar emission was an ionized, electrically neutral cloud of equal numbers of positive and negative particles. Since such a cloud is diamagnetic, it increased the geomagnetic field as it approached the Earth. This was the explanation given of the first phase of the storm and was as far as the authors succeeded in carrying the theory. They suggested that in some way the cloud must envelop the Earth and cause the major phase of the storm, but were unable to follow out the suggestion. Their Figure 9, which

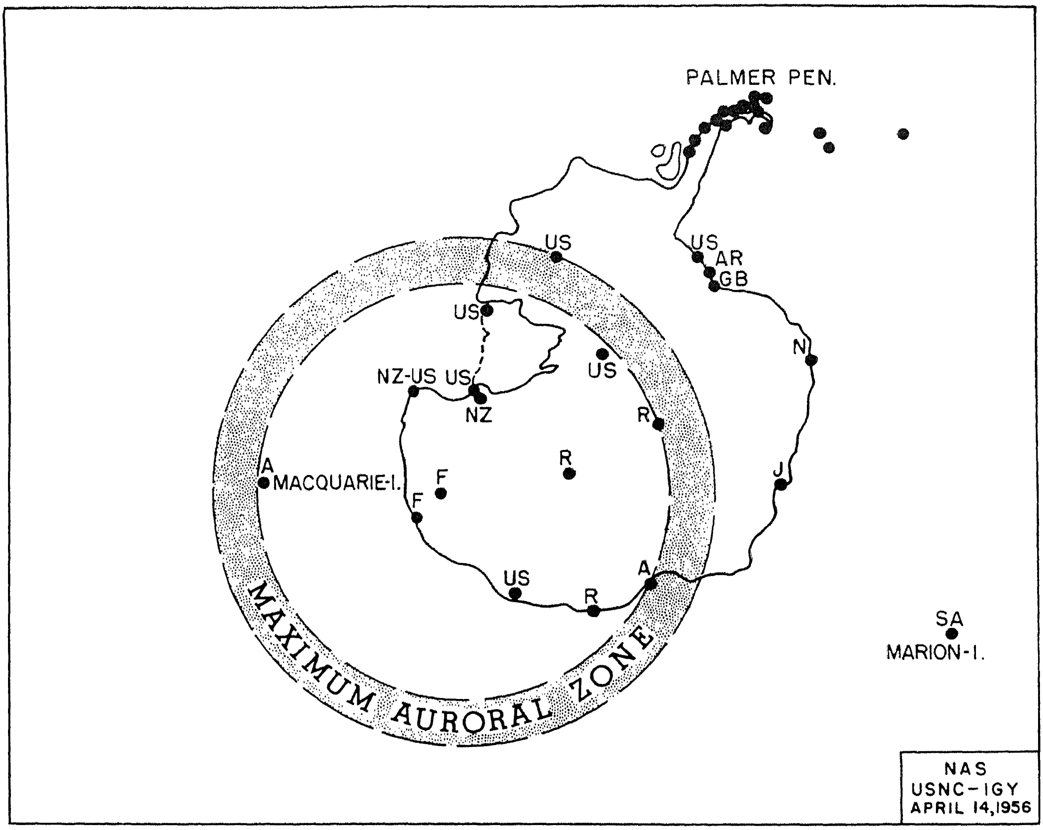

FIG. 2 – Stations in Antarctica where magnetic observations will be made during IGY

was drawn in support of the suggestion, is in error, for the signs of the electrical charges are wrongly placed.

Wulf and *Hodge* [1950] enlarged on the idea of ionospheric winds and assumed that all geomagnetic changes (except the very long period secular changes) are caused by winds in the upper atmosphere which generate electrical currents, but he did not undertake to inquire what caused the winds. *Vestine* [1954) worked out in considerable detail the upper atmospheric wind systems necessary to account for the main phase of the magnetic storm and found "some agreement with atmospheric motions inferred from radio-star scintillations and auroral motions."

Bennett and *Hulburt* [1954] invented a new theory of the aurora based on the idea that, because of magnetic self-focussing, a cloud of electrons and positive ions ejected by the Sun would develop immediately into a narrow stream of positive ions which would be bent to high latitudes by the geomagnetic field. This amounted to a revival of the solar-particle theory of the aurora of Birkland and Störmer. Although they recognized that such a stream of positive ions must also produce geomagnetic effects, they left to a later date the extension of the theory to magnetic storms. Recently *Bennett* [1954] has observed in his 'Störmertron' (an evacuated bulb in which a beam of electrons can be directed at a small magnetized sphere) effects which may explain certain features of magnetic storms. When the beam was rotated past the sphere approximately in the equatorial plane, at a certain position it was bent into a large loop by the magnetic field. The magnetic effects of this loop of current on the sphere were similar to those of the first phase of the storm. When the beam was rotated a little more, it developed into very complicated forms, and in a certain position it enveloped the sphere. In this position its magnetic effects on the sphere were similar to those of the main phase of the storm. It was also evident that the curving of the beam into the Earth was in general different at the north and south polar regions, and hence that the effect of the beam in producing magnetic disturbances and aurorae would not be the same at the two poles in either its time or space relations.

From the foregoing discussion it is seen that it is important to find out whether geomagnetic fluctuations during magnetic storms are the same, and occur simultaneously, in north and south polar regions. It is also important to find out whether the overhead currents, which according to some of the theories cause the geomagnetic fluctuations, really exist and at what level in the ionosphere they are located. In regard to the first point there is, of course, a good network of geomagnetic stations in the Arctic regions already in operation which provides fairly adequate coverage. In Antarctica an extraordinarily fine network is planned which will consist of 15 magnetic stations well distributed over the continent, and a cluster of magnetic stations on the Palmer Peninsula. These are shown in Figure 2. Argentina will operate one station, Australia one, France two, Great Britain one, Japan one, New Zealand one, Norway one, Russia three, and the United States four. There will also be magnetic stations on various islands, as the Australian one on Macquarie Island and the South African one on Marion Island. It is seen from Figure 2 that these stations should give an accurate survey of the permanent geomagnetic field in Antarctica. Their records should also provide detailed and well-spaced data on magnetic storm effects in south polar regions. From these one may construct accurate charts of the inferred overhead electrical currents, similar to Figure 1, for all the geomagnetic disturbances during the IGY period, which may then be compared with similar charts for the north polar regions in order to reveal similarities and differences. In the region inside the zone of maximum auroral frequency more land areas exist, and hence more magnetic stations will be established in Antarctic than in Arctic regions. Therefore it seems probable that inside the zone the Antarctic data will be more complete than the Arctic data, and that outside the zone the reverse will be true.

The location of the overhead currents which are supposed to cause geomagnetic disturbances may be determined by means of special observations with magnetic observatories. However, only a limited amount of information can be learned about an overhead current from a single magnetic observatory. Much more may be learned from a network of observatories. For example, if the current flows in a thin horizontal sheet, its distribution in a horizontal direction and the height of the sheet above the surface may be determined by a suitable network. The spacing of the stations in the net should be roughly of the same magnitude as the height of the sheet in order that the currents may be studied in some detail. If the overhead currents are in the ionosphere, their height above the surface is probably between 100 and 200 km. The usual spacing of the present permanent magnetic observatories, being rarely less than 1000 km, is too great. Therefore, two special networks will be installed in the Northern Hemisphere.

One of these networks will be connected with the magnetic observatory at College, Alaska, and will consist of two sets of auxiliary stations (with automatic variographs), one set to consist of four stations at about 250 km distance from College in directions north, east, south, and west, and the other set to consist of two stations about 8 km distant in directions west and south. These sets will give improved data on the time and space gradients of the magnetic disturbances from which the features of the overhead currents may be deduced.

A second network will be set up in Colorado and will consist of an east-west chain of five stations stretching about 1500 km across some of the western states, with a shorter north-south cross-arm chain of three stations. The stations will be about 300 km apart and will provide a closer network for temperate latitudes than has been available heretofore.

There will be no close-spaced network of magnetic stations in Antarctica. It is considered that results from the Northern Hemisphere networks should be studied before entering into elaborate programs in such a difficult location as the Antarctic continent.

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Clues to Ionospheric Conditions in the Southern Auroral Zone

A. H. SHAPLEY

Abstract—While there is a considerable amount of experience with short-wave radio communication via the ionosphere from the many Antarctic expeditions beginning in 1911–12, quantitative determinations of ionospheric parameters exist for only a few places and for relatively short periods of time. From sweep-frequency vertical sounding observations at these few points on the Antarctic Continent and on surrounding islands, there is evidence of at least a rough north-south correspondence of F-region critical frequencies. The operation of a rather dense network of stations during IGY will be needed for any real description or understanding of these phenomena. The objectives of a number of analyses with data from the IGY period are mentioned.

There is little direct evidence of conditions in the ionospheric regions in the vicinity of the southern auroral zone comparable to those found in its northern counterpart. We have only clues, as few stations with modern equipment have been operated on the Antarctic Continent or surrounding islands and none near the zone maximum itself. A network of stations operating simultaneously and for an extended period is needed to answer any but the simplest questions about the polar ionosphere and such data are not yet available. However, there exist very useful fragments, in time and place, for they tell that the characteristics of the ionosphere over the south polar cap tend to be similar to those in the north. Thus, although we can deduce enough to make useful predictions about radio-communications conditions, which are so essential to expeditionary work in the Antarctic, the observations are quite inadequate and insufficient to disclose any of the finer details.

Before discussing details of the southern auroral zone, some general features of the ionosphere are reviewed. The region of the high atmosphere where the density of free electrons becomes important begins at about 60 km. There is no sharp boundary or atmospheric stratification to mark the base of the ionosphere; for present purposes, however, the ionospheric D-region can be supposed to lie between about 60 and 95 km above the Earth's surface. Here the maximum density of electrons can reach a few thousand per cubic centimeter under the influence of a zenith Sun, and probably much more in the auroral zones during an important magnetic disturbance. An unusually high density of electrons in this range of ionospheric heights produces blackouts of short-wave radio communication, because the radio waves are absorbed and so prevented from reaching the higher reflecting layers. Between 100 and 120 km, and sometimes also up towards 200 km, there are strata or layers of fairly high electron density, composing the E region. Some are strongly controlled by the Sun, others are greatly affected by strong electric currents and atmospheric turbulence and perhaps by the influx of extra-terrestrial particles. The F region of the ionosphere begins at about 200 km and is composed of one or two layers 30 to 100 km or more thick. This region has the largest electron density of any of the ionospheric layers. The radio frequencies used in long distance communication are usually selected to make optimum use of the reflecting properties of the F region layers. Above about 400 km not much is known about the electron density of the atmosphere; if there are additional layers, they must usually be less dense and therefore likely not to be observed by the commonly used techniques.

Echo-sounding of the ionospheric layers, introduced by Breit and Tuve in 1926, has become the basic patrol experiment for determining the worldwide characteristics of the ionosphere and their many variations. Modern automatic sweep frequency ionosondes map out a sort of electron density profile above the observing station. The electron density is deduced from the radio frequency of the probing pulse which is reflected from any given ionospheric height. The highest frequency which is reflected by an ionospheric layer, the critical frequency, is a measure of the layer's maximum electron density, and this is a characteristic widely used to describe the time and geographical variations of the ionosphere. The heights of the layers may be deduced from the time delay of the echoes; this is a 'virtual' height, since it is reckoned by multiplying the time delay by the speed of light, and is subject to large corrections in particular cases.

A great deal of work has gone into studying and mapping ionospheric characteristics in the north polar regions, with important beginnings made during the Second Polar Year, 1932–33. It was early determined that the zone of maximum occurrence-frequency of visual aurora, first outlined from observations in the First Polar Year, 1882–83, also was a zone of symmetry for many properties of the ionospheric layers. This zone, in the north, is roughly 23° from the geomagnetic pole, and is particularly marked by large and erratic ionospheric changes at all levels on time scales of minutes or hours. The observations can often best be interpreted in terms of clouds of ionization rather than homogeneous strata, with rapidly fluctuating density and large apparent motions. Many of these phenomena are closely associated with geomagnetic storms and auroral displays. Inside the zone, the ionospheric characteristics tend to be more stable, but distinctly different from the lower latitudes.

The southern observations have confirmed that the same sort of phenomena are occurring at both polar caps. Beyond this we cannot say much. It is the filling in of these details which is an important objective of the observing program planned for the International Geophysical Year.

The first instance of radio communications in the Antarctic, and therefore, the first bit of ionospheric data, seems to have been accomplished by Mawson in 1911-12 from Terre Adelie to Tasmania by way of a relay station on Macquarie Island. Communication was on a wavelength of 600 meters, which we now interpret as demonstrating the existence of the ionospheric E region. Very little of a research nature appears to have been done until 1928 when the first echo soundings in the Antarctic, by Hanson of the Naval Research Laboratory at Little America I, demonstrated the presence of the E and F regions during the Antarctic winter night. At the same time, Berkner made radio signal-strength measurements, recording some effects of magnetic storms. Later expeditions continued ionospheric work on a small scale.

Modern techniques were utilized in Antarctica on the High Jump expedition in 1946–47. An automatic sweep-frequency ionospheric sounder, although of early design and borrowed from an experimental laboratory, was operated in Antarctic waters for about two months and provided the first detailed measurements of the diurnal variation of critical frequencies of the ionospheric layers. The observing period also included two magnetic storms and the ionospheric conditions during these storms exhibit the expected characteristics of high absorption, blanketing sporadic E, and depressed F2 critical frequencies. While the period of observation was brief, the experiment provided further clear evidence that no major discrepancies existed between ionospheric conditions on the north and south polar caps.

Similar observations were taken on the *Commandant Charcot* in 1949–50 and again in 1950–51. These shipboard measurements contributed to our knowledge at that time. However, compared to observations at fixed stations, their usefulness is so limited that it is now difficult to include them in a description of the south polar cap. Ionospheric critical frequencies are subject to very large and erratic variations from day to day, both on account of magnetic storm and other less well defined effects. These are superposed on top of several smoother variations—large diurnal fluctuations, seasonal changes, and changes which go along with the 11-year solar activity cycle. Ionospheric characteristics are also a strong function of magnetic latitude. These can all be identified and described by statistical analysis, but not from a few days' observations unless there are nearby some stations for which statistics are available for a much longer period. Thus to interpret the shipboard observations in otherwise uncovered parts of the world, we must make major assumptions regarding the representativeness of the sample.

In 1951 an ionospheric sounding station was operated at Terre Adelie [*Bougin*, 1953] and provided the first extended coverage on the Antarctic Continent. Regular observations are available from Deception Island and Port Lockroy in the Palmer Peninsula beginning in 1952, but because of the eccentricity of the auroral zone, these stations are in relatively low magnetic latitudes, corresponding approximately to Tasmania. More important for ionospheric studies of the southern auroral zone are the stations at Campbell Island, starting in 1944, and Macquarie Island, beginning 1950. These stations, however, are still far outside the auroral zone, while Adelie Land is well within. Thus there are no extended observations from the vicinity of the zone maximum, and indeed there is major uncertainty in the location of the maximum.

The available soundings data from geomagnetic latitudes near the southern auroral zone is indicated in Figure 1. The stations were operated as follows: Terre Adelie—Laboratoire National de Radioelectricité, France; Macquarie and Hobart—Commonwealth Observatory, Australia; Campbell Island—Christchurch Observatory, New Zealand; Ross Sea—Department of the Navy, United States; Port Lockroy and Falkland Island—Department of Scientific and Industrial Research, England; and Deception Island—Ministerio de Marina DGMCM, Argentina. Data have been received by the Central Radio Propagation Laboratory of

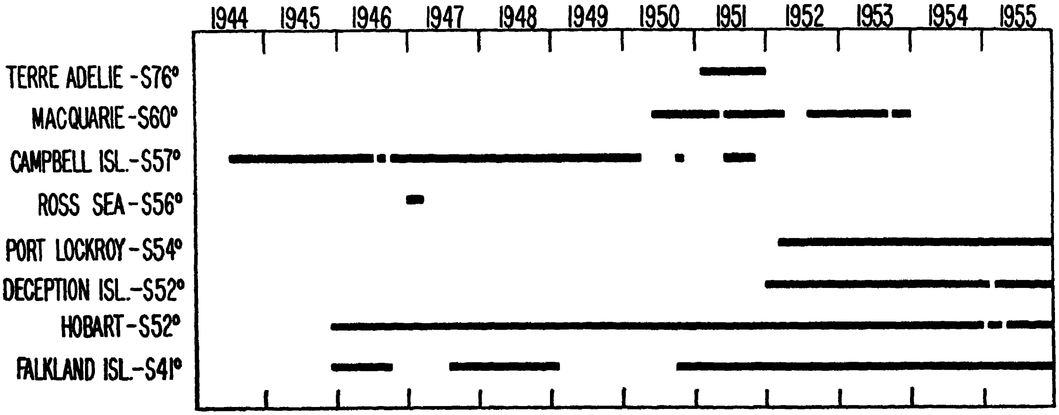

FIG. 1 – Ionospheric soundings available from southern auroral and subauroral stations

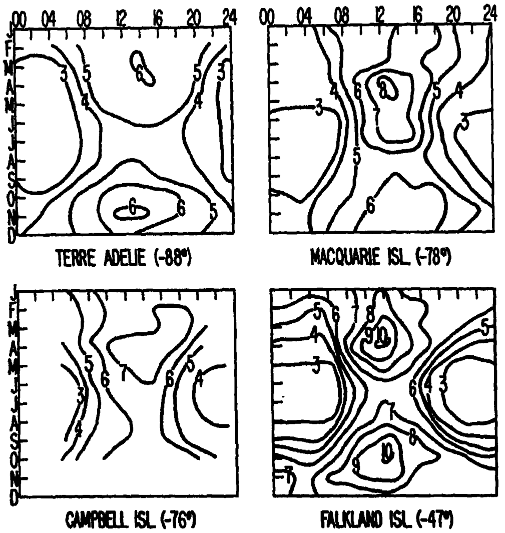

FIG. 2 – foF2 (in Mc/sec), monthly median diurnal variations, 1951

the National Bureau of Standards as part of a regular international exchange of data and published in the CRPL-F series publication.

The year 1951 is appropriate for illustrations of these ionospheric conditions since the Terre Adelie, Macquarie, and Campbell Island stations were all operating. The monthly median diurnal variations of F2 layer critical frequencies for these stations, and for a higher latitude station, Falkland Islands, are shown in Figure 2 in contour diagrams which also demonstrate the large seasonal changes. The coordinate indicated for each station is magnetic dip angle: the F2 critical frequency is sensitive both to the zenith angle of the Sun and to parameters of the Earth's magnetic field. The former is prominent in the diagram for Falkland with abrupt increases at sunrise. At Campbell Island, a station at nearly the same geographic latitude but much larger magnetic dip, the critical frequencies are as much as 30 pct lower during daytime during all but the winter season and the summer effect is much less pronounced. The effect shows even better in comparison with Macquarie Island, although it is only three degrees farther south than Falkland in geographic latitude. At Terre Adelie, just south of the Antarctic circle, the absolute values of critical frequencies and the amplitude of the diurnal variation is still less, as expected from its higher geographic latitude and magnetic dip.

In testing the similarity between the Northern and Southern Hemispheres, one should compare stations whose magnetic and geographic coordinates are the same. A systematic difference would remain even with such an ideal pair of stations, since one must compare like seasons, and during the six month lag thus introduced, a solar cycle effect will have entered. If one chooses magnetic dip as the geomagnetic parameter, the closest northern counterpart to Terre Adelie is Baker Lake in the Northwest Territory of Canada. The monthly median diurnal curves of F2 are shown in Figure 3 for the year 1951 for Terre Adelie and six months later for Baker Lake. For many months the curves are very similar, although there appears to be a systematic tendency for the Baker Lake curves to be more peaked at midday in winter than Terre Adelie and to have a smaller amplitude of diurnal variation in summer. Some of this may be the effect of instrumental errors or observational selection, but it could also be that the magnetic dip is not the suitable parameter for such a comparison. This is a question which can be answered only with more observational material.

The north-south similarity can also be examined by graphs like Figure 4 which gives the relationship

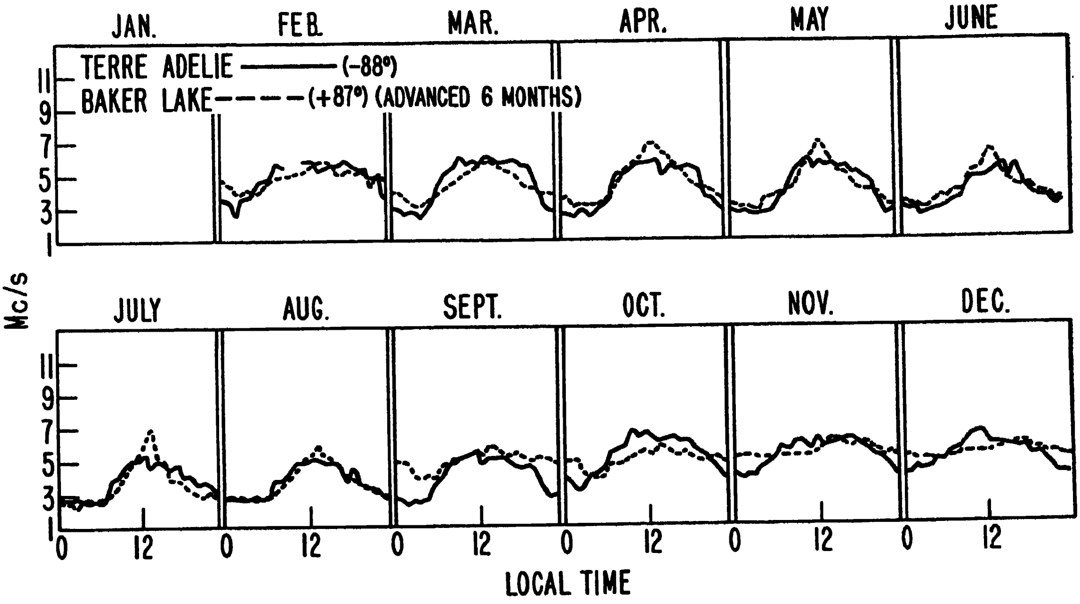

FIG. 3 – foF2 monthly median, 1951

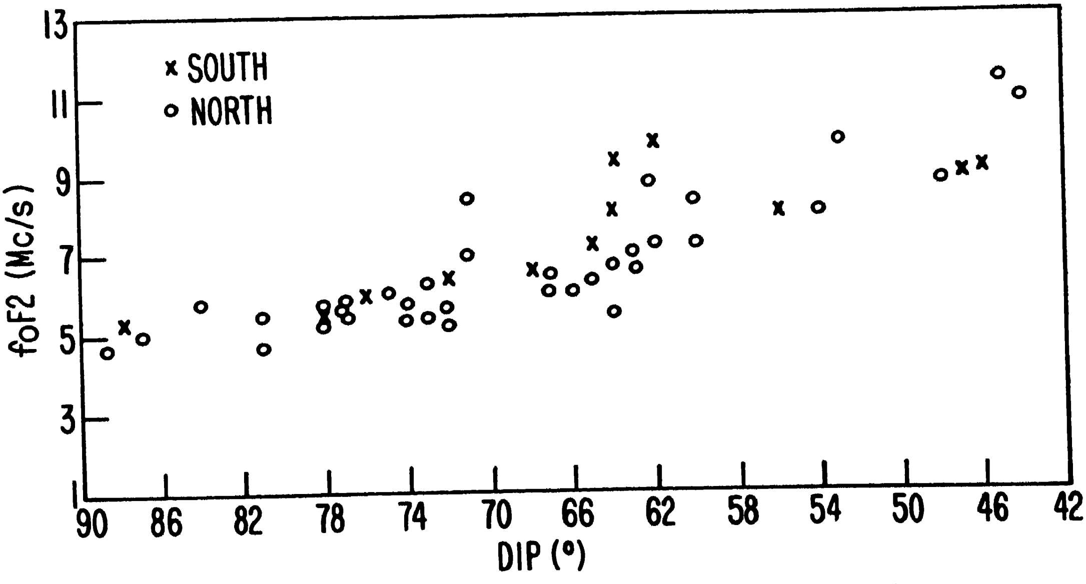

FIG. 4 – foF2 as a function of magnetic dip (local noon medians, Sep. 1951)

between F2 critical frequencies and magnetic dip for a single hour for an equinoctial month noon in September 1951. Here we make the assumption that for the same solar zenith angle, the ionosphere is the same in spring as in fall. All available stations are shown. The many discrepant points indicate we have not properly handled the relative influence of solar and geomagnetic effects, but there are certainly no clear discrepancies between the two hemispheres.

It is to be expected that the understanding of the ionosphere near the southern auroral zone will be increased markedly from the IGY period when ionospheric soundings will be obtained simultaneously for 18 months at a dozen or more sites on the Antarctic continent, covering a wide range of geomagnetic latitudes and longitudes. Some of the particular objectives of these programs are:

(1) Maps of mean characteristics of the D, E and F regions over the south polar cap. These are

also a practical necessity for expedition communications, thus far largely planned on the basis of northern observations and assumptions of symmetry.

(2) Location of southern auroral zone from observations of radio wave absorption and other ionospheric characteristics. These results, complementing deductions from geomagnetic and auroral measurements, are most important for the theory of high atmosphere storms and the role of solar particles in causing or triggering these effects.

(3) North-south comparisons of average properties of ionosphere. If there are significant differences in the levels of ionization, it may be evidence for interaction of the upper with the lower atmosphere, where there is a large systematic difference in temperature and other meteorological properties.

(4) North-south correspondence of ionospheric storm phenomena. As in the case of aurora and geomagnetism, the simple questions of whether effects are simultaneous in detail in the northern and southern auroral zones remains unanswered.

(5) Effect of prolonged periods of darkness and insolation. The atmospheric processes during the long polar night and polar day present quite different conditions than the 24-hour daylight cycles in lower latitudes and offer a unique experiment for a station at the geographic pole.

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The Aurora Australis and Related Phenomena

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Abstract—The tentative geographic distribution of the occurrence of aurora in the Southern Hemisphere, as derived from the results of many expeditions, are described. Comparisons of those results with those for the Northern Hemisphere are made. Relationships to geomagnetic and ionospheric phenomena are described. Some opportunities afforded by the observing programs of the International Geophysical Year are discussed.

Introduction—The aurora australis has been studied since quite early times. The early collection of auroral observations by *Fritz* [1873] included results for the period 1670 to 1872. *Boller* [1898] showed from these results that the increase in auroral frequency polewards evinced in middle latitudes continued far to the south. *Davies* [1931] was later able to demonstrate that the polar data could be roughly fitted to a circular auroral zone centered about the southern magnetic axis pole. In later studies *White* and *Geddes* [1939; *Geddes*, 1939], and *Vestine* and *Snyder* [1945], extended this work. The latter estimated the position of the auroral zone from magnetic data and found this reasonably compatible with the auroral observations. Their results were examined locally, mainly for the area south of Australia, by *Jacka* [1953; *Thomsen*, 1952], who obtained findings roughly compatible with those of Vestine and Snyder. In addition, he examined the relationship of the aurora to indices of magnetic activity.

It is also well known that the aurora, whether in the Northern or Southern Hemispheres is related in its incidence and character to other solar and geophysical phenomena [*Chapman* and *Bartels*, 1940; *Harang*, 1951]. Thus, near the auroral zone, large magnetic intensifications (or bays) often appear suddenly with the onset of intensified aurora [*Harang*, 1951; *Heppner*, 1954] accompanied by marked radio wave absorption (or blackouts) near and below the E region [*Wells*, 1947]. The electric fields driving the bay electric currents appear to move the ionized F region bodily upwards or downwards at such times. Also, more general relationships among magnetic storms, aurora, and sunspots [*Chapman* and *Bartels*, 1940], and also with solar radio noise [*Dodson* and others, 1953] have been observed.

It is the purpose of the present paper to review some of the observations of the aurora australis and related phenomena. In particular, an attempt will be made to mention a few matters of interest to those who will be concerned with global studies of auroral observations of the International Geophysical Year (IGY) 1957–58.

Auroral forms—For hundreds of years, observers have tended to distinguish quiescent auroral forms from others actively moving, diffuse forms from rayed or striated forms, and colors other than the familiar 5577 A green, when in evidence. In 1930, at Oslo, a more specific nomenclature was provided for use during the International Polar Year, 1932–33. The forms included were homogeneous quiet arcs (HA), often extending from the eastern to the western horizon, like a broad rainbow, with a diffuse upper and sharper lower boundary. Homogeneous bands (HB) are similar but less regularly shaped, with breadths varying along the length of the band, and sometimes with folds. Figures 1 and 2 show auroral bands observed in Norway by Störmer. Pulsating arcs (PA), in which whole arcs might light up and disappear and reappear in seconds, have been mentioned but they must be very rare if they occur. Pulsating surfaces or patches (PS) are common. Often listed is the glow (G), or feebly illuminated area, often low in altitude to observers not very close to the auroral zone, and of indefinite patterns. When there is ray structure, there may be rays arcs (RA), draperies (D), and isolated patches of rays (R); when rays are overhead since they are aligned along or nearly along the geomagnetic field, the rays appear to radiate from a zenith, and the form then is called a corona (C). It has no special claim to recognition as an auroral form other than its indication that ray forms are overhead. Finally, a rare form known as flaming aurora (F) is seen, but because it occurs rarely, there probably is some confusion in existing records listing its observation. According to the atlas of auroral forms, by definition it comprises transverse (straight) bands of illumination (with dark bands in between) moving as a progressive wave patterns for example, approaching the zenith like a series of ocean waves approaching the shore. The bands may be parallel to normally appearing homogeneous arcs.

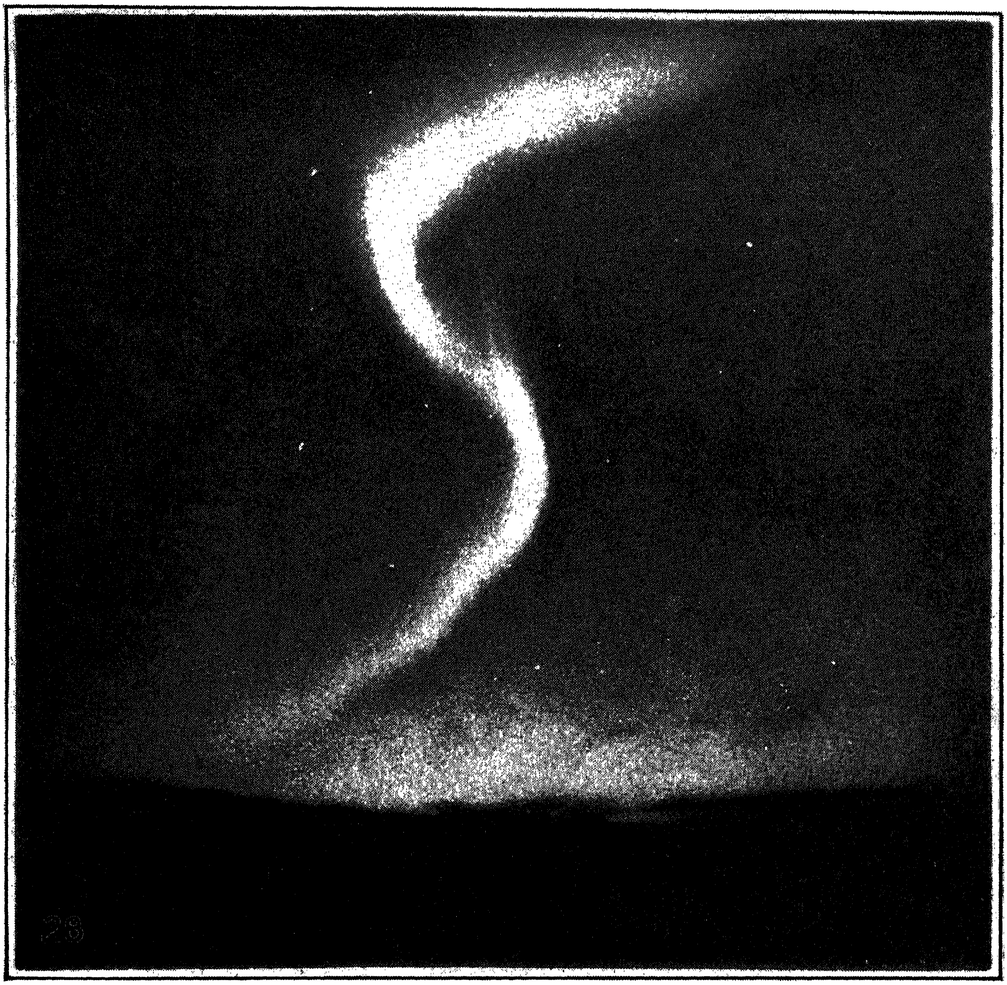

FIG. 1 – Twisted band with ray structure, October 14, 1935 (Störmer)

Colors are usually a greenish yellow, but occasionally they are also red, violet, green, and blue.

Auroral forms tend to appear in a well-defined sequence with time. The usual sequence described is often:G → HA → HB → RA → R → C → PS in whole or in part. This is partly a manifestation of the broadening of the auroral belt or zone, as in the case of C, and there are many exceptions. For instance, all forms may be in evidence at once, during a strong and complex display. A major opportunity to define the typical sequences in events and forms of aurora is afforded by the IGY.

The heights of homogeneous arcs is of the order 100–110 km (Fig. 3), whereas ray forms extend from near this level to heights as great as 1000 km [*Chapman* and *Bartels*, 1940; *Harang*, 1951]. These heights do not seem to vary much with either latitude or longitude.

The average daily frequency of occurrence of the aurora australis—Figure 4 shows the estimated percentage frequency of days with occurrence of aurora, on clear dark nights, as derived by *Vestine* and *Snyder* [1945]. It is assumed, as in the Northern Hemisphere, that aurora are visible from the auroral zone every clear dark night. The position of this auroral zone was deduced from geomagnetic data. It was assumed that the electric currents flowing in the upper atmosphere are stronger in regions where the electric conductivity is enhanced by the presence of aurora. Many magnetic stations were so far away that most estimates were uncertain, especially from 270°E through 0° to 90°E. The auroral data, however, show reasonably good agreement with results estimated from geomagnetic data. The spacing between the isochasms has been assumed similar to that defined by actual auroral data, for the northern hemisphere. It is

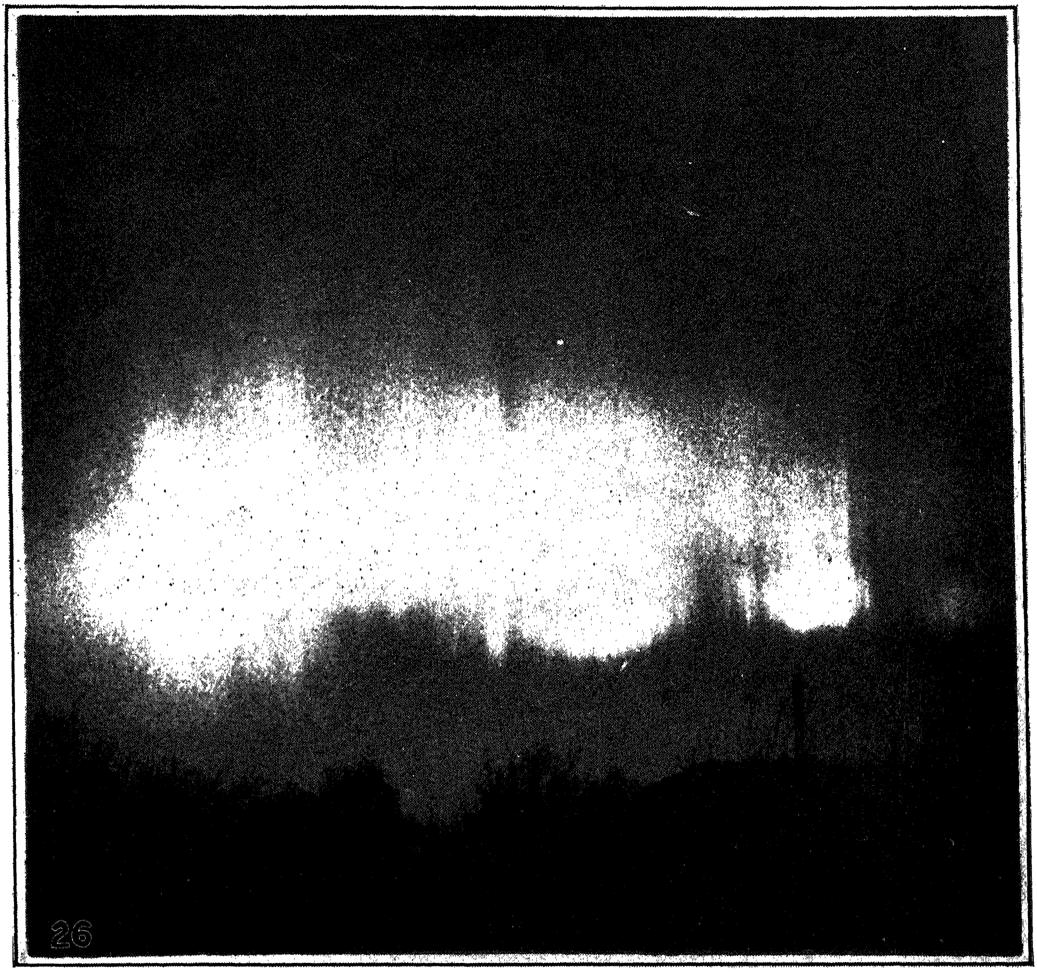

FIG. 2 – Band with ray structure, October 14, 1935 (Störmer)

also clear from these results (for example, three years of data at Little America yield percentages of 83, 55, and 92) that a single year of observations is normally insufficient to define isochasms other than in crudest terms. Moreover, if estimates are based only upon observed instances of aurora at the zenith, there would be so few data that little could be done about the global features. On the other hand, knowledge of the auroral form and its elevation above the horizon, from adequately recorded observations would permit drawing the isochasms with greater resolution. This would provide an improvement, though the main change would probably only be that of crowding the isochasms slightly towards the zone or line of maximum auroral frequency.

It is also necessary that journals of cloud or cloud amount be kept by auroral observers, or insured available; otherwise, percentage frequencies will be in error.

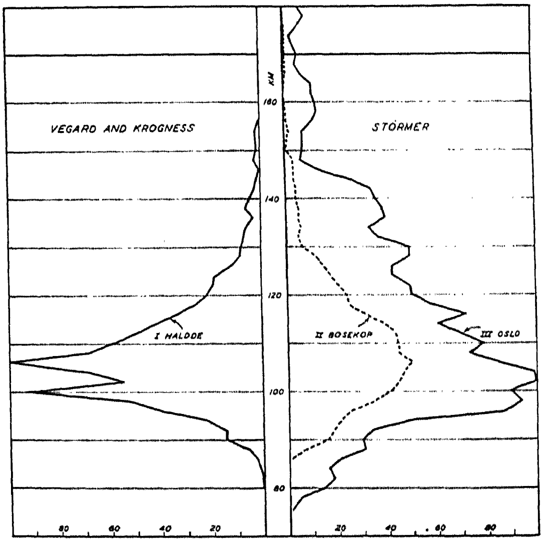

FIG. 3 – Total distribution, all forms, of lower limits for auroral heights

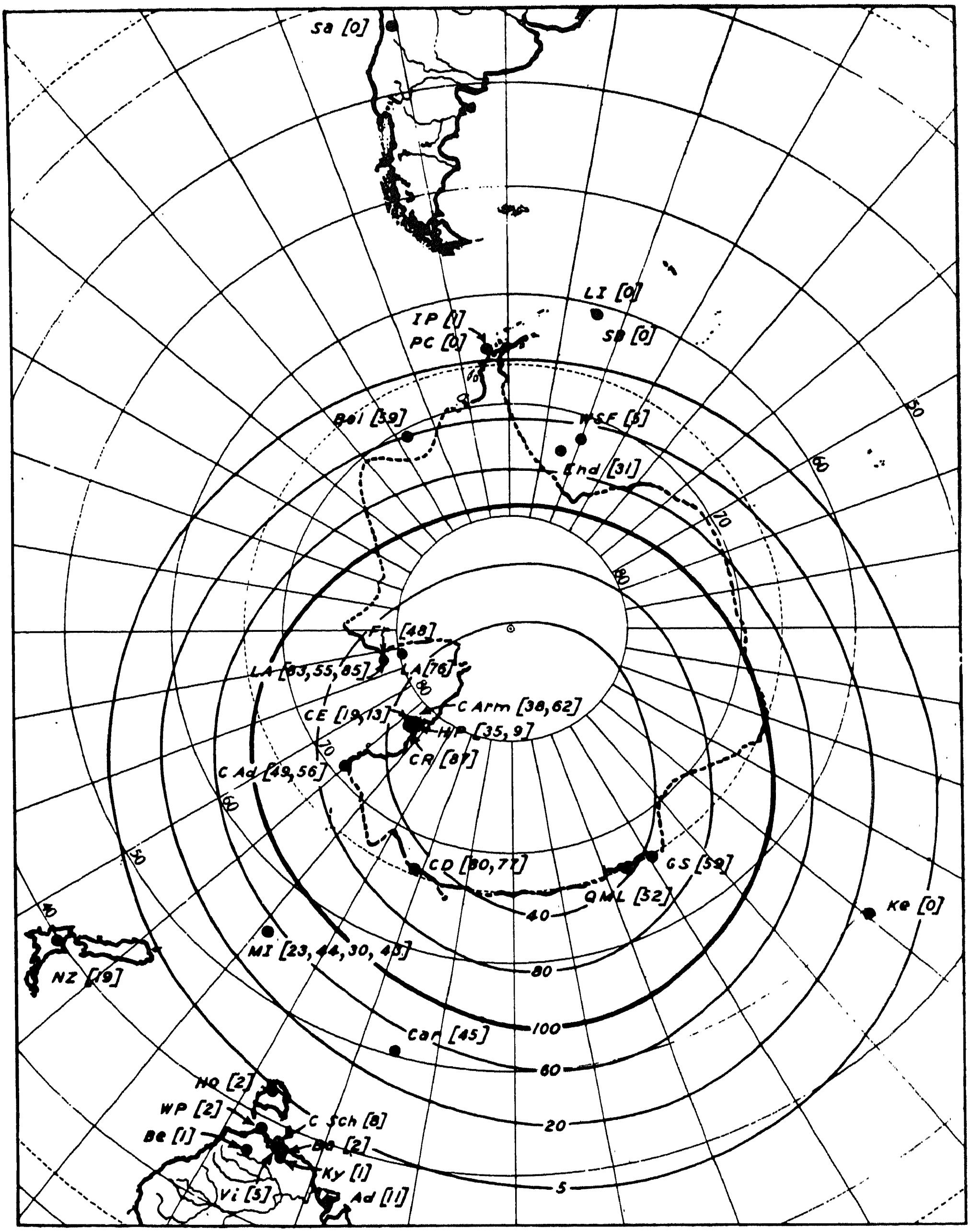

Fig. 4 – Estimated percentage—frequency of days with occurrence of aurora, clear, dark, nights, high latitudes, Southern Hemisphere (stations shown by letters as indicated in text)

Table 1 lists the auroral stations and their particulars for various years, 1841–1940, previously discussed more fully by *Vestine* and *Snyder* [1945]. Table 2 lists the abbreviations shown in Figure 3 that were used for the auroral stations.

The hourly frequency of the occurrence of aurora—Figure 5 shows auroral data for Little America. When auroral stations are sufficiently close to the auroral zone, or when many years of observations are available, it may be possible to determine the hourly isochasms of aurora. In the Antarctic there have as yet been no auroral stations located close to the auroral zone. Figure 6 includes hitherto unpublished results for both northern and southern stations. The diurnal variation for a few of those

TABLE 1 – *Auroral stations and particulars, various years, 1841–1940*

Station	Geographic		Geomagnetic		Available period observation		Number of days				No. of obs'ns aurora	No. of obs'ns used	Percentage frequency
	South latitude, ϕ	East longitude, λ	South latitude, Φ	East longitude, Λ	From	To	Available obs'ns	Cloudy	Sunlit				
									Yearly	Excluded			
	°	°	°	°									
Little America, Advance Base	80.1	196.0	75.6	316.7	Apr. 8, 1934 July 1, 1934	May 28, 1934 Aug. 24, 1934	76	14(a)	207	0	47	47	76
Little America, West Base I	78.6	196.1	74.6	312.0	Mar. 21, 1934	Sep. 15, 1934	147	36(a)	199	0	92	97	83
Little America, West Base II	78.5	196.1	74.5	311.9	Apr. 21, 1940	Sep. 16, 1940	121	26(a)	199	0	52	52	55
Little America	78.6	196.2	74.6	312.1	Apr. 3, 1929	Sep. 14, 1929	165	(c^+)	199	0	122	122	92
Framheim	78.6	196.4	74.5	312.4	Apr. ?, 1911	Sep. 11, 1911	163	26(d)	199	0	66	66	48
Cape Armitage, *Discovery*	77.8	166.8	79.0	294.4	Apr. 1, 1902	Sep. 30, 1902	183	46(c)	193	11	56	49	42
Cape Armitage, *Discovery*	77.8	166.8	79.0	294.4	Apr. 1, 1903	Sep. 30, 1903	183	17(c)	193	11	99	96	68
Hut Point	77.8	167.0	78.9	295.5	Apr. 1, 1911	May 12, 1911	42	19(c)	193	0	8	8	38
Hut Point	77.8	167.0	78.9	295.5	Mar. 16, 1912	May 1, 1912	47	13(c)	193	12	2	2	10
Cape Evans	77.6	166.4	78.9	293.2	Apr. 1, 1911	Sep. 30, 1911	183	36(c)	191	10	26	26	21
Cape Evans	77.6	166.4	78.9	293.2	Apr. 1, 1912	Sep. 30, 1912	183	42(c)	191	10	17	17	14
Cape Royds	77.5	166.2	78.9	292.4	Mar. 26, 1908	Oct. 2, 1908	191	60(b)	191	16	103	100	87
Weddell Sea, *Endurance*	73.8	314.9	62.9	14.4	Mar. 10, 1915	Sep. 9, 1915	184	61(b)	168	0	38	38	31
Weddell Sea, *Deutschland*	72.0	320.0	61.4	18.3	... 1911	... 1912	182	126(b)	158	0	3	3	5
Cape Adare	71.3	170.2	73.9	276.1	Apr. 1, 1899	Sep. 30, 1899	183	44(d)	153	0	73	68	49
Cape Adare	71.3	170.2	73.9	276.1	Feb. 27, 1911	Sep. 30, 1911	216	49(c)	153	12	89	87	62
Belgica	70.8	272.6	59.7	348.5	Mar. 11, 1898	Sep. 10, 1898	184	80(e)	150	0	61	61	59
Cape Denison	67.0	142.7	75.5	235.2	Feb. 13, 1912	Oct. 18, 1912	249	69(b)	119	8	139	138	80
Cape Denison	67.0	142.7	75.5	235.2	Mar. 1, 1913	Oct. 24, 1913	238	100(b)	119	0	106	106	77
Queen Mary Land	66.3	95.0	77.0	150.6	Apr. 9, 1912	Sep. 16, 1912	161	47(d)	115	0	60	60	57
Gauss-Station	66.0	89.6	76.1	141.9	Feb. 19, 1902	Feb. 18, 1903	365	74(c)	112	112	134	106	65
Ile Petermann	65.2	295.9	53.7	3.5	Feb. 13, 1909	Oct. 30, 1909	260	120(c)	105	0	1	1	1
Port Charcot	65.1	296.1	53.6	3.6	Jan. 8, 1904	Feb. 15, 1905	405	68(c)	104	104	4	1	0
Laurie Island	60.8	315.0	50.0	18.0	... 1904	... 1912	3285	......	62	62	0	0	0
Scotia Bay	60.7	315.4	50.0	18.3	Apr. 1, 1903	Feb. 21, 1904	327	78(c)	62	62	1	1	0
Macquarie Island	54.9	158.9	61.5	243.3	May 13, 1912	Nov. 6, 1912	178	108(c)	...	...	24	13	25
Macquarie Island	54.9	158.9	61.5	243.3	Apr. 9, 1913	Oct. 25, 1913	200	127(c)	...	...	49	32	48
Macquarie Island	54.9	158.9	61.5	243.3	Dec. 6, 1913	Nov. 26, 1914	356	252(c)	...	...	71	30	33
Macquarie Island	54.9	158.9	61.5	243.3	Dec. 7, 1914	Nov. 26, 1915	355	267(c)	...	...	91	38	47
Carnegie	50.5	135.6	60.8	212.7	Feb. 28, 1916	Mar. 31, 1916	33	...(f)	...	...	10	10	45
Kerguelen	49.4	69.9	57.4	127.6	Jan. 8, 1902	Feb. 15, 1903	404	122(c)	...	...	1	1	0
Hobarton	42.9	147.5	51.7	224.6	... 1841	... 1848	365	...	...	...	6	6	2
New Zealand	39.8	175.5	43.9	254.2	... 1933	... 1939	365	...	...	...	68	68	19
[a] Wilson's Promontory	39.8	146.4	48.8	222.5	Aug. 1, 1882	Aug. 1, 1883	365	...(f)	...	...	6	6	2
[a] Cape Schank	38.5	144.9	47.7	220.4	Aug. 1, 1882	Aug. 1, 1883	365	...(f)	...	...	20	20	8
Victoria, Australia	38.0	146.0	47.0	221.5	... 1859	... 1862	365	...(f)	...	...	13	13	5
[a] Ballarat	37.5	143.9	46.8	219.0	Aug. 1, 1882	Aug. 1, 1883	365	...(f)	...	...	4	4	2
[a] Kyneton	37.3	144.4	46.6	219.6	Aug. 1, 1882	Aug. 1, 1883	365	...(f)	...	...	3	3	1
[a] Beechworth	36.4	146.7	45.4	222.0	Aug. 1, 1882	Aug. 1, 1883	365	...(f)	...	...	3	3	1
[a] Adelaide	34.9	138.6	44.9	212.4	Oct. 1, 1882	Dec. 31, 1882	92	...(f)	...	...	7	7	11
Santiago	33.4	289.3	22.0	358.5	Nov. 17, 1849	Sep. 13, 1852	1032	...	...	..	1	1	0

[a] Only aurora contemporaneous with magnetic storms listed.

TABLE 2 – *List of abbreviations for auroral stations, southern hemisphere*

Station	Abbr.	Station	Abbr.	Station	Abbr.
Adelaide	Ad	Cape Schank	CS	Little America	LA
Ballarad	Ba	*Endurance*	End	Laurie Island	LI
Beechworth	Be	*Deutschland*	Deu	Macquarie Island	MI
Belgica	Bel	Framheim	Fr	New Zealand	NZ
Cape Adare	CAd	*Gauss*-Station	GS	Port Charcot	PC
Cape Armitage	CAr	Hobarton	Ho	Queen Mary Land	QML
Cape Denison	CD	Hut Point	HP	Santiago	Sa
Cape Evans	CE	Ile Petermann	IP	Scotia Bay	SB
Cape Royds	CR	Kerguelen	Ke	Victoria	Vi
Carnegie	Car	Kyneton	Ky	Wilson's Promontory	WP

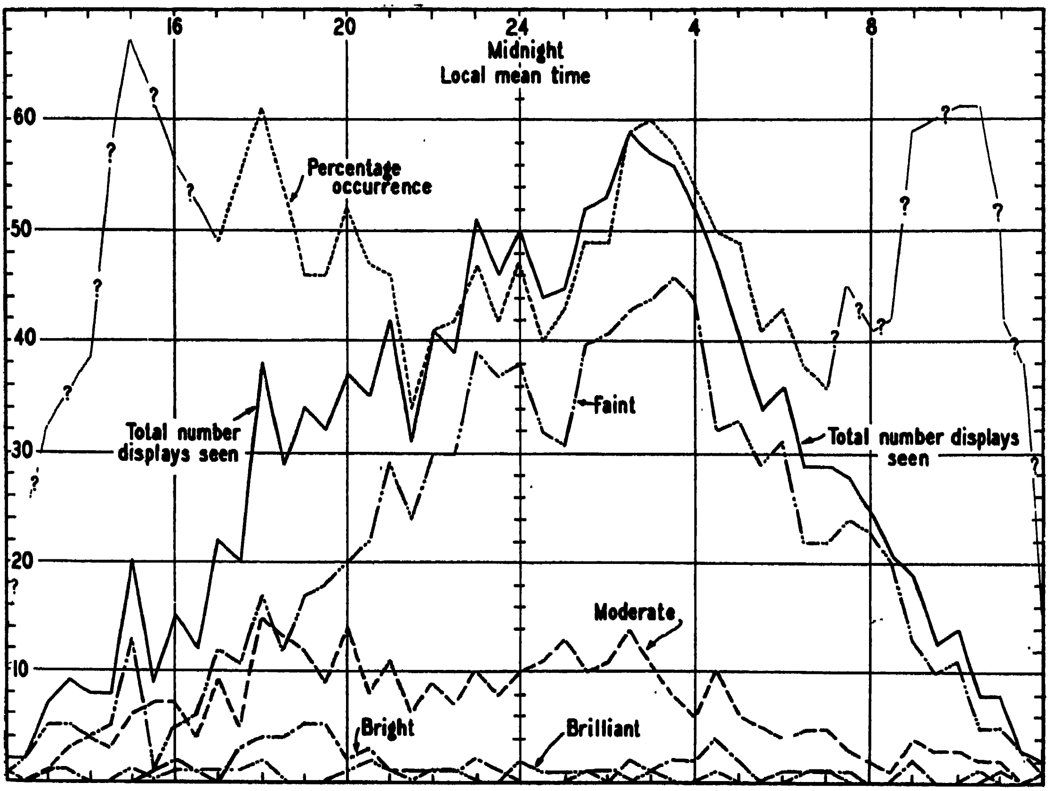

FIG. 5 – Aurora australis, Little America, April to September 1929

for north polar regions has been derived previously by *Vegard* [1952], *Hulburt* [1931], *Fuller* and *Bramhall* [1937], and others. The results here have been rederived and adjusted for poor visibility, daylight conditions, and for cloudiness, in approximate accord with procedures described previously by *Vestine* [1944]. Near the auroral zone the percentage frequency attains a maximum of 50–60 pct of all clear hours. This maximum is attained near magnetic midnight or a little earlier. As one proceeds within the auroral zone polewards, the maximum may appear later, as shown by Little America in 1929, and Kingua Fjord in 1882–1883. Near the geomagnetic pole, as shown by the considerable data for Fort Conger, 1881–1883, a midnight maximum is not shown. This may also be the case in high southern latitudes, from the results for Gauss-station, 1902–03. An exception is shown for Gjoahavn, though it may be that observations made after midnight were less

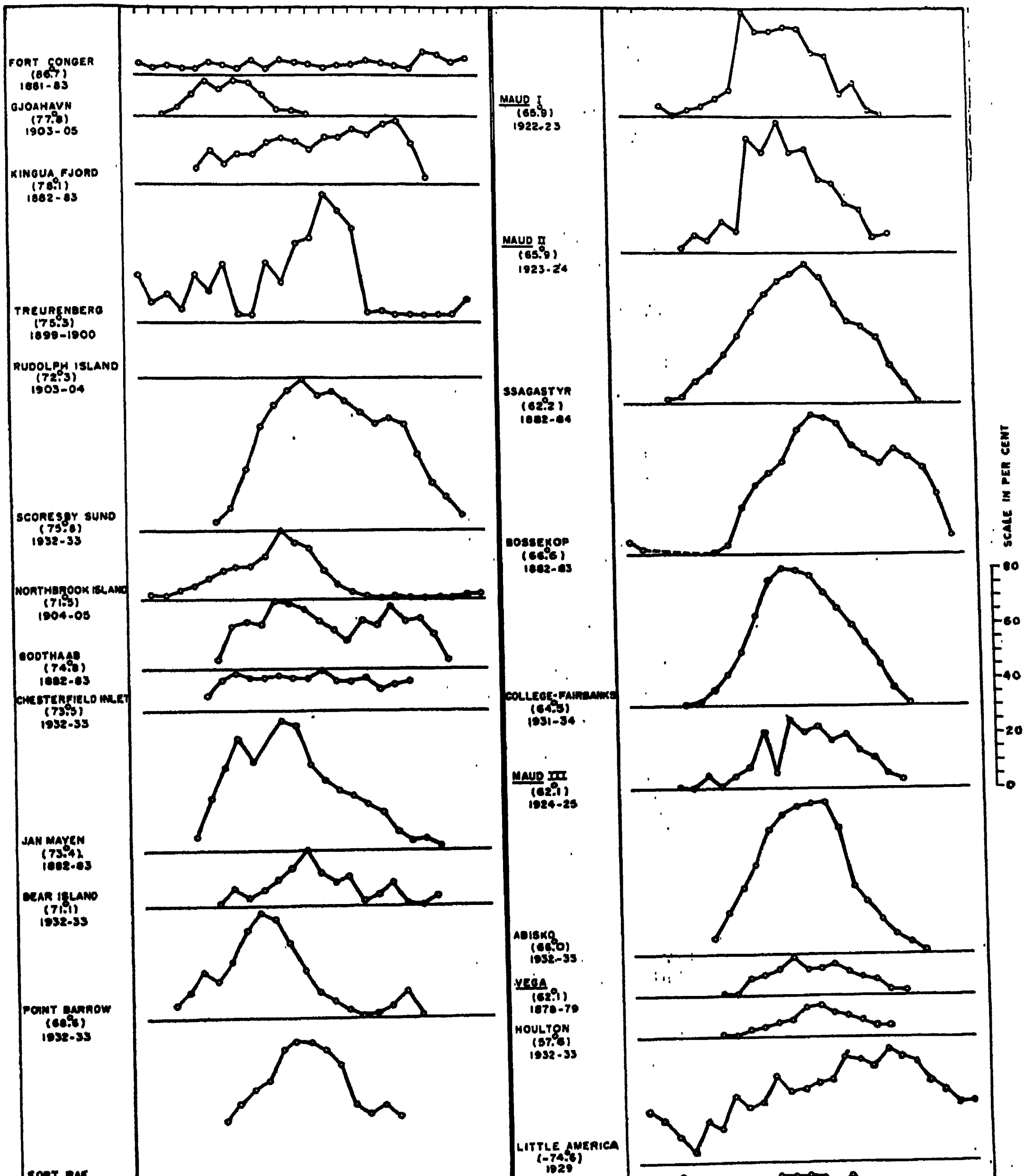

Fig. 6 – Daily variation of occurrence of aurora in per cent of sufficiently dark possible hours of observation, Northern and Southern Hemispheres (geomagnetic latitudes indicated in parentheses)

complete. In any case the diurnal variation at southern stations appears to resemble that for northern stations. It will be possible to examine this question more closely when data become available for stations considerably closer to the southern auroral zone. As *Harang* [1951] has remarked, a single year cannot provide much useful information on diurnal variation unless the station is very near the auroral zone.

There also appears to be a tendency for stronger displays to occur before midnight with weaker, more diffuse forms after midnight. These matters

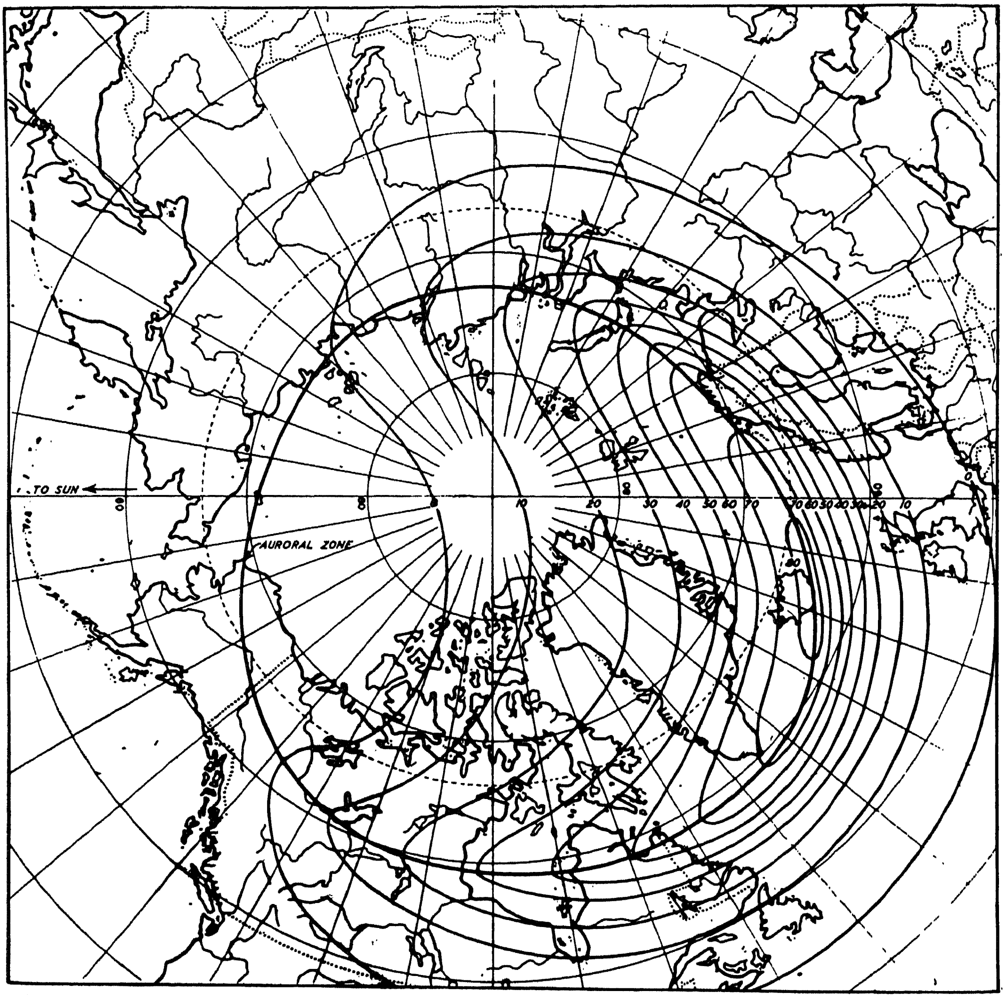

FIG. 7 – Estimated percentage—frequency of hours with occurrence of aurora, clear, dark nights, high latitudes, Northern Hemisphere, for 0^h GMT

have been extensively discussed for the aurora australis by *Davies* [1931]. Figures 7–10 show tentative isochasms drawn for 0, 6, 12, and 18 hours GMT, for the Northern Hemisphere. These have been published previously but incorrectly, the times 6 and 18 hours GMT being reversed in the title [*Vestine* and others, 1947]. The writer is indebted to D. F. Martyn for kindly pointing out this error in the titles. These figures give a rough and smoothed version, or interpolated version, of the results of Figure 6.

The estimated isochasms are of necessity somewhat crude, at distances well removed from the auroral zone, but it is believed that they may afford a good first approximation.

The auroral spectrum and air glow—The auroral spectrum of the aurora borealis has been the subject of extensive inquiry by many workers [see cited by *Chapman* and *Bartels*, 1940; *Harang*, 1951] and can only be mentioned briefly here. There has been little spectrographic study of the aurora australis, but this will be one of the major projects of IGY. The principal line is the 5577 A green line, explained by McLennan and Shrum as due to a forbidden transition of atomic oxygen. Similarly, there arise the red lines 6300 A and 6363 A, examined by Vegard. These three lines give the green and red colors of the aurora. In addition to these three atomic lines of oxygen, there are many bands belonging to the band spectrum of the nitrogen molecule, which have been studied by Vegard, Kaplan, Meinel, and many others, who have made notable contributions to our knowledge of aurora and the upper atmosphere. The relative

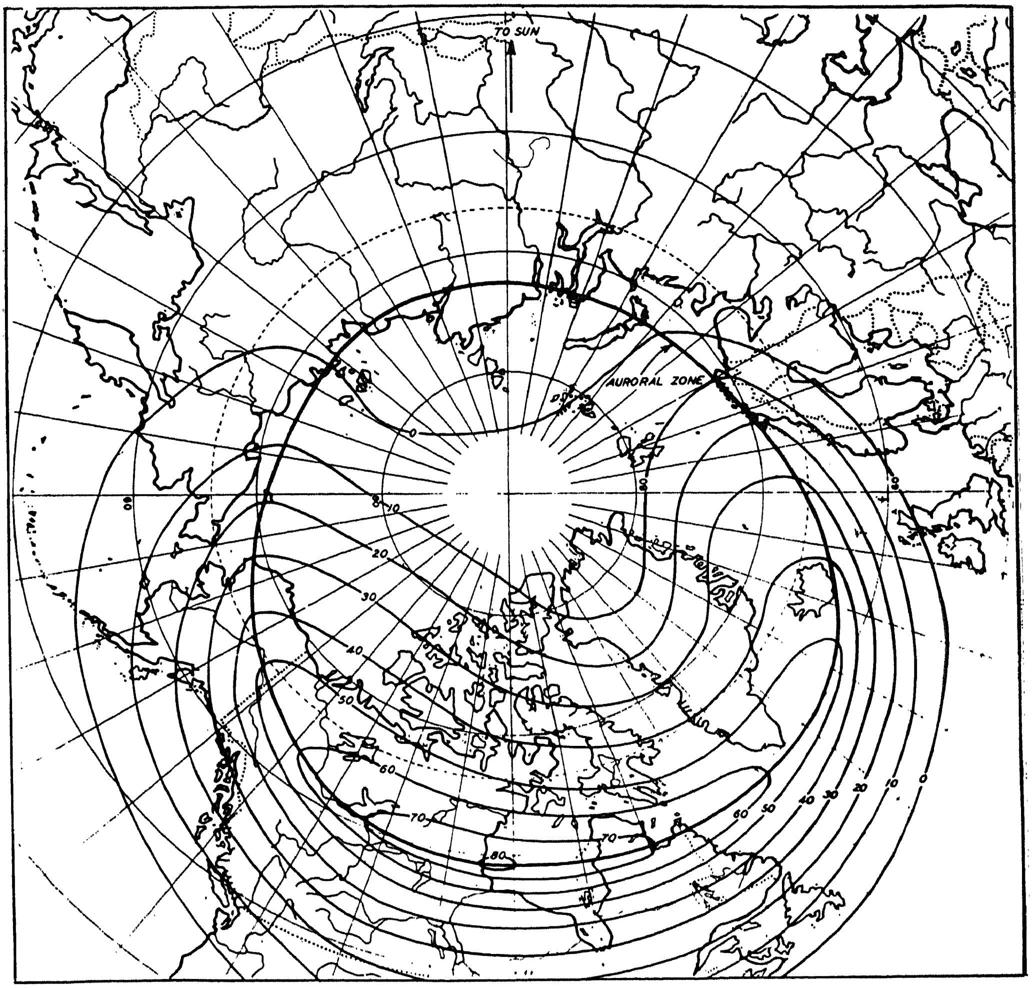

FIG. 8 – Estimated percentage—frequency of hours with occurrence of aurora, clear, dark nights, high latitudes, Northern Hemisphere, for 6h GMT

intensities of lines depends upon the height of the emitting aurora, and the spectra hence are of great importance in the study of constituents of the upper atmosphere and their motions. Störmer has extended such information to heights as great as 1000 km, using the spectra of sunlit aurora *Chapman* and *Bartels*, 1940; *Harung*, 1951].

Observations on the aurora and air glow in the Southern Hemisphere, at Capetown and Canberra, have been reported by Lord Rayleigh and Spencer Jones [*Chapman* and *Bartels*, 1940], who found that the emission near 5577 A varies with sunspot cycle. This line of the air glow produces from six to nine per cent of the total brightness of the night sky. The Vegard-Kaplan bands between 3500 A and 5000 A are the most intense of the bands. The relative intensities of the various lines and bands of the air glow differ from those for the aurora.

The heights of the emitting regions responsible for the air glow have been studied recently by *Roach* and *Meinel* [1955]. They find that more observations are necessary, although they refer to the lower ionosphere as the location of sources, and quote extensive literature on the subject.

These matters have recently been discussed more fully by *Chamberlain* and *Meinel* [1954], *Bates* [1954], and *Nicolet* [1954]. A valuable earlier summary of interest is that of *Hewson* [1937].

Relationships to solar and magnetic phenomena—Magnetic disturbance and aurora are often closely linked, as shown in Figure 11 due to Heppner [1954]. *Harang* [1951] has indicated other typical

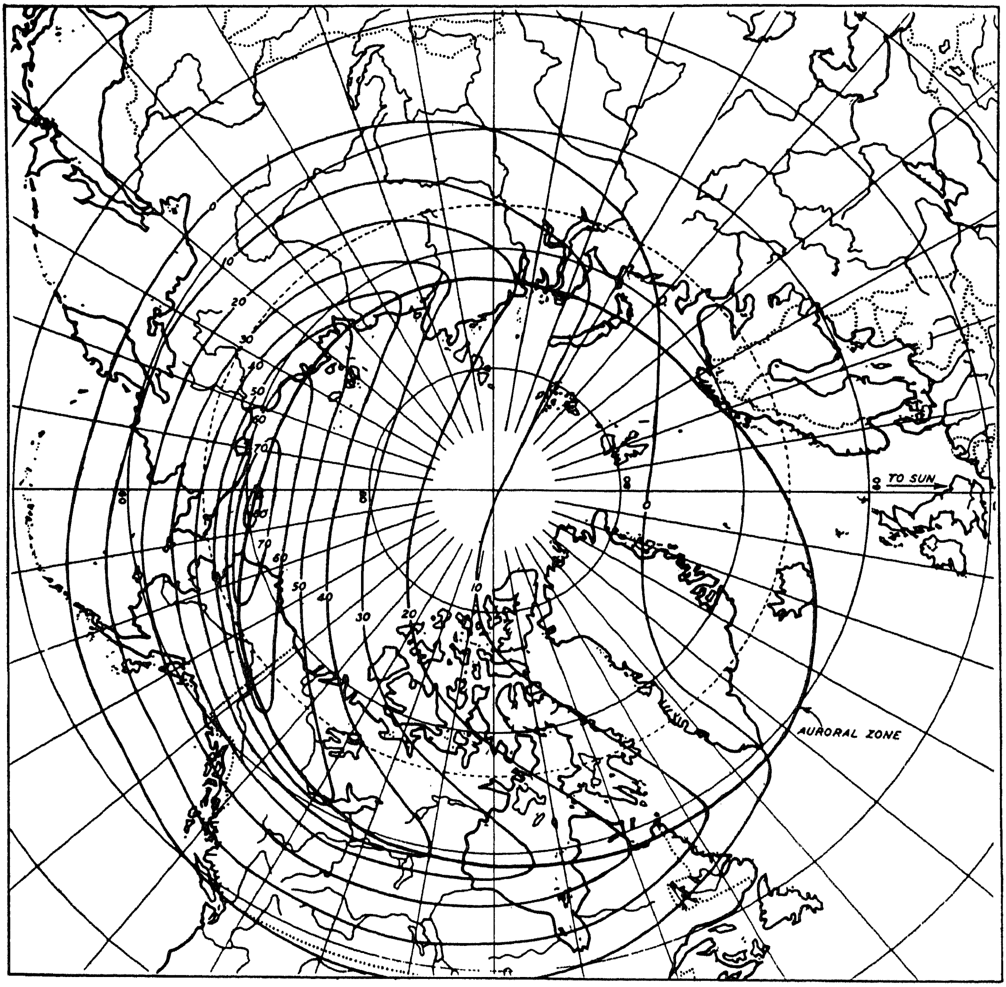

Fig. 9 – Estimated percentage—frequency of hours with occurrence of aurora, clear, dark nights, high latitudes, Northern Hemisphere, for 12^h GMT

examples. During the great magnetic storm of May 14–15, 1921, aurora were seen at Samoa (13°8 S) at the time of greatest magnetic disturbance, expansion of the auroral zone being characteristic of great magnetic storms. Between the auroral zones, in either hemisphere, there is an annual variation in auroral frequency showing maxima in March and October, and minima near the solstices [*Chapman* and *Bartels*, 1940; *Harang*, 1951]. Near the auroral zone, where aurora are seen almost daily, account has to be taken of intensity in order to exhibit dependence on season. Figure 12 shows the variation of the aurora australis with sunspot cycle, noted by *Boller* [1898]. As in geomagnetism, the equinoctial maxima in auroral frequency must be related to terrestrial causes which are as yet quite obscure. Auroral rays also lie rather closely along the lines of force of the geomagnetic field, and, as has already been seen, there is a tendency for isochasms to conform, even though oval, to circles of geomagnetic latitude.

Electric current systems and aurora—Figure 13 shows that the daily mean horizontal vector disturbance D_m tends to be nearly perpendicular to the average direction of homogeneous arcs, in the aurora borealis [*Vestine*, 1938]. The natural inference is that the electric currents affecting the daily means of horizontal magnetic intensity tend to flow along or parallel to homogeneous auroral arcs in high latitudes. It should be noted that these vectors are usually not perpendicular to the auroral zone, nor to parallels of geomagnetic latitude. The averaged geomagnetic data are obtained from years of observation that are not

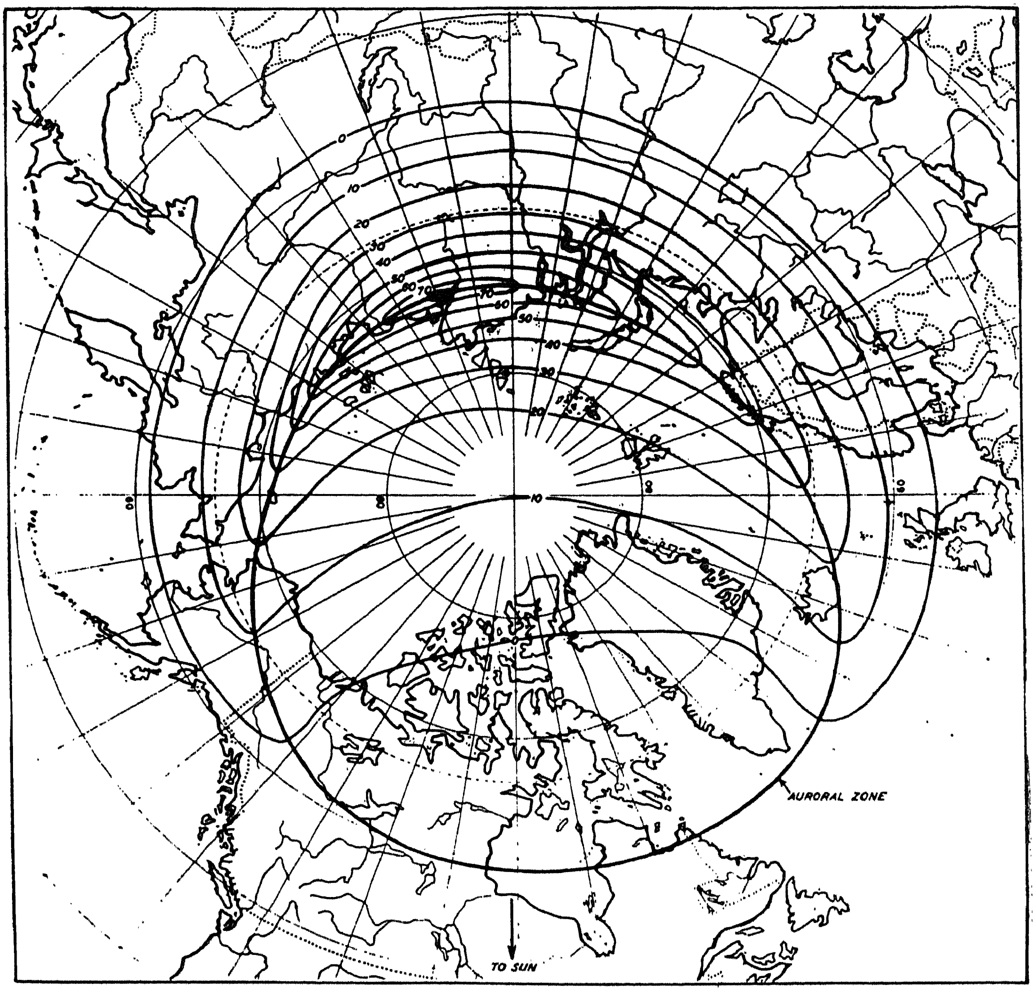

FIG. 10 – Estimated percentage—frequency of hours with occurrence of aurora, clear, dark nights, high latitudes, Northern Hemisphere, for 18^h GMT

the same as those used for aurora. These points should also be investigated for the aurora australis.

Figure 14 shows a typical current-flow pattern appropriate to a magnetic bay [*Silsbee* and *Vestine*, 1942], which may accompany conditions like those described by Heppner in Figure 11. The bay disturbance is clearly due to an electrojet at the auroral zone. This means there are electric forces present which drive the current-system [*Fukishima*, 1953]. If the electric conductivity in auroral regions were known, for a time of magnetic bay, it would be possible to estimate from the current and its distribution the required electric forces to produce the bay. Then in turn, there could be estimated the accelerating action upon the ions and electrons present, and their ultimate velocities. Obviously, an important question must be whether or not such forces could drive electrons (or ions) upward or downward to produce aurora. A very interesting question is that of whether such auroral production would be a secondary effect, the primary effect being due to incoming protons which seem actually detected by *Vegard* [1939], *Gartlein* [1950], and *Meinel* [1951], within homogeneous auroral arcs, from Doppler shift in H_α. These protons are usually ascribed to solar sources. There are a number of rudimentary developments of corpuscular theories which attempt to explain the auroral displays in terms of particles of solar origin. The first important corpuscular theory was that of *Birkeland* [1908, 1913] which was greatly extended in the valuable later studies of Störmer, dealing with very rarefied streams or the motions of individual particles [*Störmer*, 1930; *Chapman* and *Bar-*

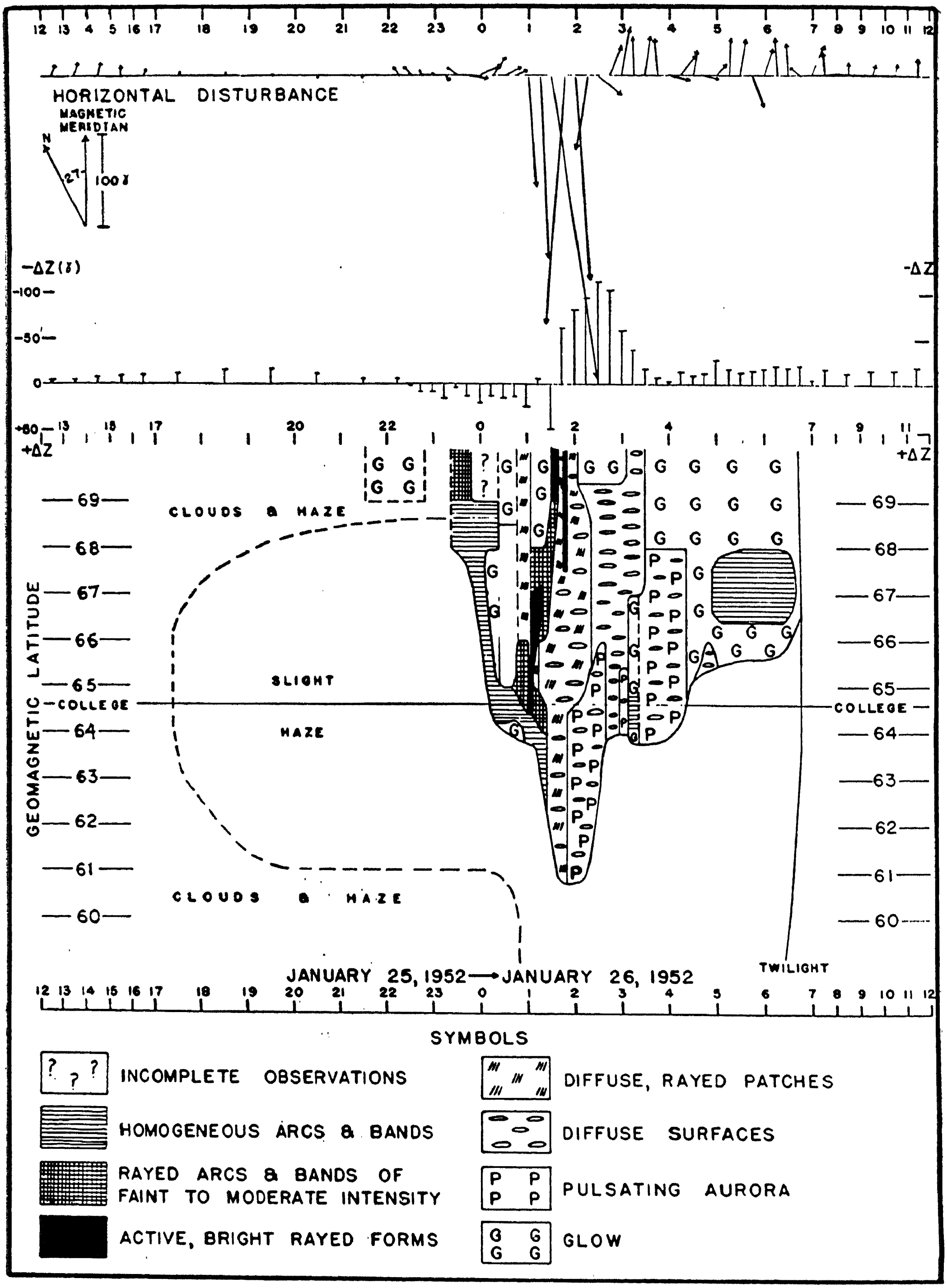

FIG. 11 – Relation of magnetic disturbance and aurora (after Heppner)

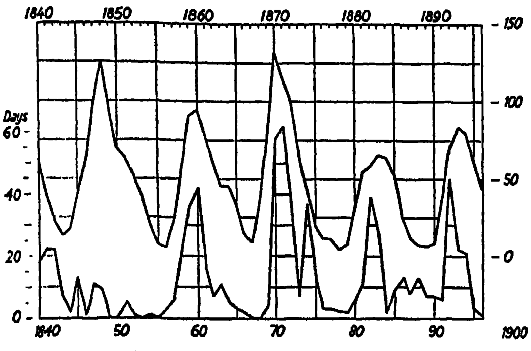

FIG. 12 – The number of days per year on which southern lights (aurora australis) were seen, in 1840–96 (lower curve) compared with the relative sunspot numbers (upper curve) (after Boller)

tels, 1940; *Harang*, 1951]. Streams of particles have been dealt with by *Chapman* and *Ferraro* [1931, 1932, 1933, 1940, 1941; *Ferraro*, 1952, 1953] (with extensions by Martyn) in a number of carefully executed investigations which may serve as a basis for a theory of aurora. According to them electric fields in solar streams are small. *Alfvén* [1950] on the other hand considers the effect of electric fields in space (acting across the Earth), generated by the motion of solar streams in a solar magnetic field. According to his calculations, which have been questioned by *Cowling* [1942] there should be produced auroral zones, with aurora as a consequence of electric discharge phenomena. *Bennett* and *Hulburt* [1953] have outlined a beam theory of aurora and magnetic disturbance. According to this hypothesis, the concentration of particles required to yield auroral displays is facilitated by a self-focussing action upon the stream constituents. According to *Ferraro* [1954], the Chapman-Ferraro theory includes more tenable bases for constructing a theory of aurora. Recent results of *Simpson* and others [1956] showing a pronounced lack of symmetry in cosmic ray intensity relative to the magnetic equator seem to imply extra-terrestrial forces not yet considered, and show the need for extensive revisions of all of these theories. The allowed regions for auroral particles would be modified by these current-systems flowing above the Earth. Similar findings of *Thambyahpillai* and *Elliot* [1953], which have been extended by Forbush tend to support this view since they seem to show the likely existence of considerable deflecting forces in regions surrounding the Earth; these forces are important enough to affect cosmic rays so that their effect upon solar streams of low energy protons or other ionized particles should be even more profound. Another interesting possibility, which has been actively studied by *Wulf* [1953], is that high speed zonal winds may generate electric fields adequate to drive protons downward with suitable energies. The possibility of a dynamo theory of the magnetic changes was mentioned by Chapman in 1927 and later by *Vestine* and *Chapman* [1938]. The most detailed and careful calculations on this matter are those of *Fukishima* [1953], and *Matsushita* [1953], who found that they could reproduce the current pattern of Figure 13, if a patch at the auroral zone were ionized by an incoming beam of high energy particles. *Vestine* [1954] has examined the electrical effects of a vertical gradient in the wind speed of growing zonal winds such as those considered by *Wulf* [1953], in a region of high electric conductivity. He concluded that this might provide a generator similar to that of the Swann mechanism for the generation of cosmic rays [*Swann*, 1953]. The positive particles would be driven downward, and parallel to the geomagnetic field and the electrons upward and along the geomagnetic field at a higher latitude, as observed in Figure 1, if we suppose that particles move downward in homogeneous bands and upward in rays. It was also suggested that hydromagnetic waves would be generated and might be propagated upward, and that this might be an explanation of the progressive wave motions in flaming aurora.

The diurnal variation in auroral activity has been examined in recent years using radar techniques. *Gerson* [1955; *Currie* and others, 1953] has recently summarized the principal results. It is found that the diurnal variation in the occurrence of ionized aurora seems to be similar to that of the visual aurora. The maximum frequency seems to occur before midnight when visually observed aurora outside the auroral zone seem more intense. The ion densities in aurora may be of the order 10^8, according to some of these results. Similar studies should of course be made for the aurora australis.

Widespread auroral displays are associated with ionospheric as well as magnetic storms, and even modest displays may affect the ionosphere sufficiently to influence radio communications. Attempts to explain these effects as a consequence of electric fields generated in the E region, and in polar regions have met with encouraging success in the hands of Martyn, Hirono, Maeda, Matsushita, Briggs, Maxwell, and others [*Physical Society*, 1954]. The electric fields originating in the

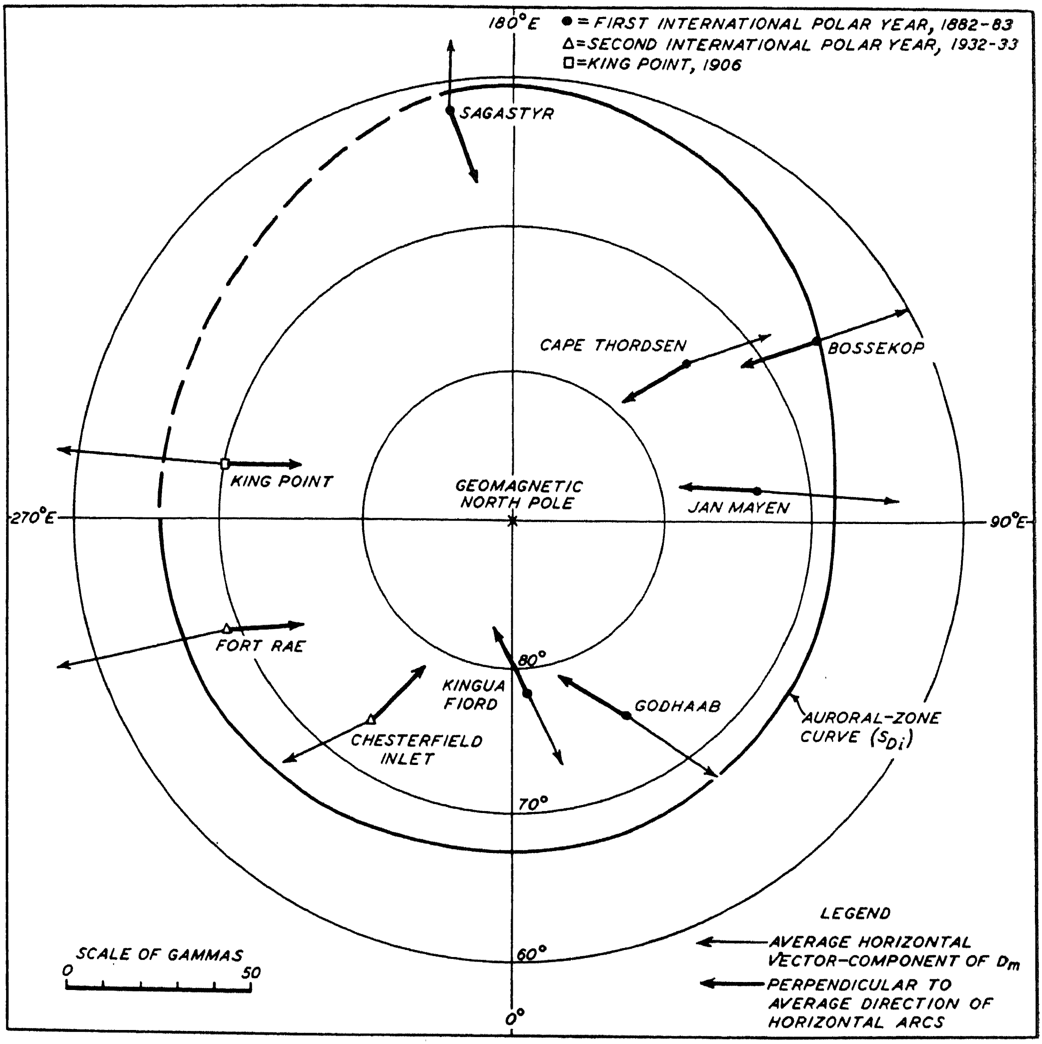
180°E
● = FIRST INTERNATIONAL POLAR YEAR, 1882-83
△=SECOND INTERNATIONAL POLAR YEAR, 1932-33
□=KING POINT, 1906
SAGASTYR
CAPE THORDSEN
BOSSEKOP
KING POINT
GEOMAGNETIC NORTH POLE
JAN MAYEN
270°E
90°E
FORT RAE
80°
KINGUA FIORD
GODHAAB
AURORAL-ZONE CURVE (S_{Di})
CHESTERFIELD INLET
70°
LEGEND
AVERAGE HORIZONTAL VECTOR-COMPONENT OF D_m
PERPENDICULAR TO AVERAGE DIRECTION OF HORIZONTAL ARCS
SCALE OF GAMMAS
0
50
60°
0°

Fig. 13 – Comparison of average directions of horizontal components of D_m with perpendiculars to auroral arcs

auroral zone appear to extend significantly even to the equator, where they produce drift motions in the F region; consequently, their effect upon auroral displays themselves must be inferred. In fact, it seems likely that the drift of aurora and radio star scintillation effects to the west before midnight, and to the east after midnight, must be due to similar crossed electric and geomagnetic fields.

Antarctic aurora and airglow program, 1957–58—During the period of observation of the IGY, a number of nations will greatly extend the existing information respecting the aurora and airglow in the Antarctic. The United States program anticipates observations visually, with patrol spectrograph, and all-sky camera at Little America, Byrd Station, the Pole, Weddel Sea, Knox, and at Adare. In addition, a scanning spectrometer and low-power radar installation is expected to operate at Little America. The spacing between stations will ensure a network of stations having good spacial coverage.

Certain stations will operate with identical equipment at both Arctic and Antarctic locations which are near a line of magnetic force of the geomagnetic field, so that simultaneity of events in either hemisphere may be examined. These new sources of observational material will thus add greatly to the store of information respecting the aurora and related phenomena.

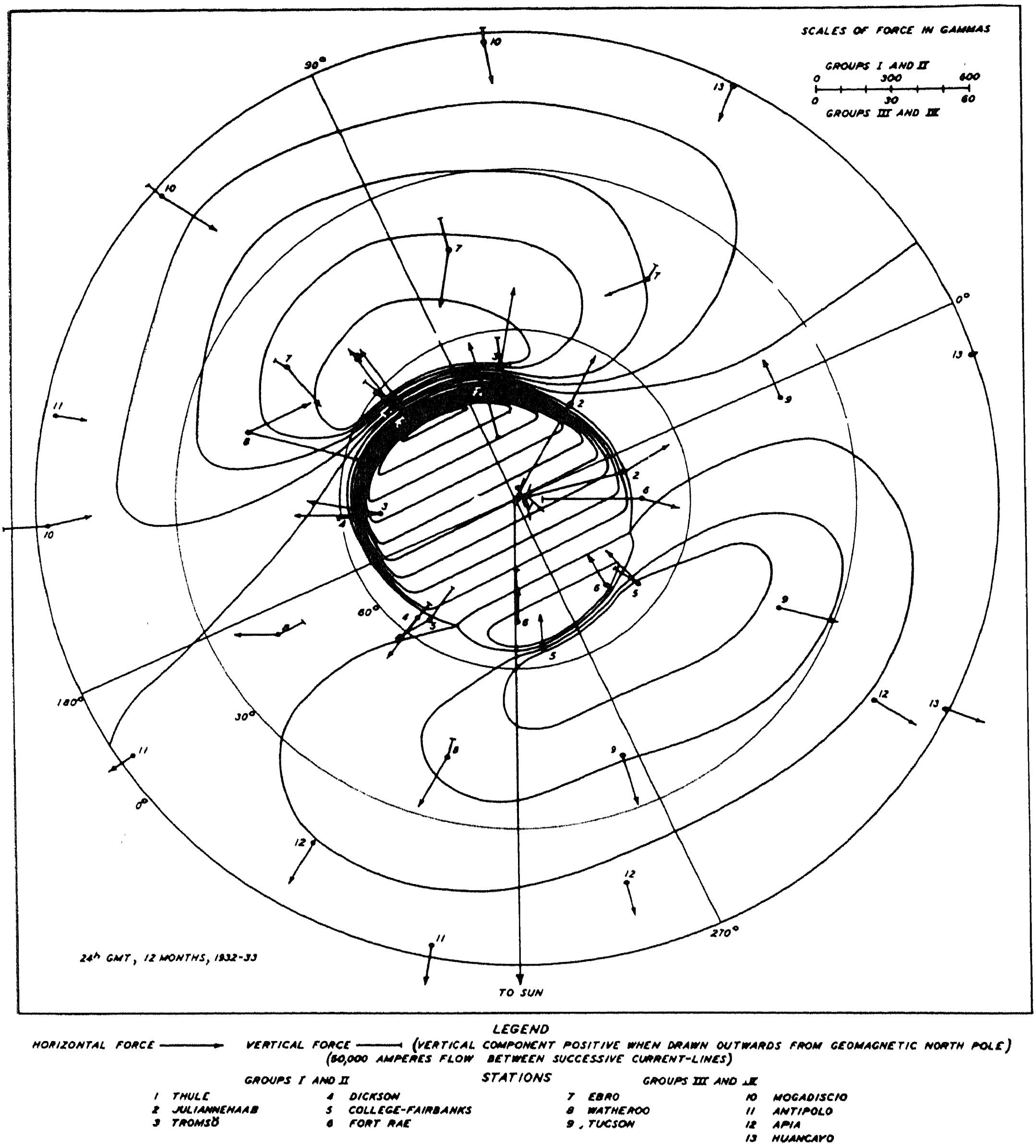

Fig. 14 - Mean three-hour disturbance vectors of magnetic bays centered at 21h, 24h, and 3h GMT (tentatively corrected for induced currents) and corresponding average electric current-system of height 150 KM, view from above geomagnetic North Pole

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Cosmic Ray Experiments Derived from Recent U. S. Antarctic Expeditions

J. A. SIMPSON

Abstract—Cosmic-ray particles have been used as probes to investigate the distribution of the Earth's permanent magnetic field extending into the interplanetary space. The experiments were performed on the U.S.S. *Atka* and the U.S.S. *Arneb* during the two U. S. Antarctic Expeditions in 1954–55 and 1955–56, respectively. These results along with additional data show that this outer magnetic-field distribution is strikingly different from the results based upon magnetic measurements extrapolated from the surface of the Earth. Since the magnetic moment of the Earth's dipole field is inclined with respect to the axis of rotation, the cosmic-ray evidence suggests that the field distortion arises from the interaction of the magnetic field with a highly ionized interplanetary gas. These results also bear on the problem of defining geomagnetic coordinates for incoming charged particles. Preliminary results concerned with (a) the eccentricity of equivalent geomagnetic dipole fields, (b) the lattitude effect of cosmic radiation in the Southern Hemisphere, and (c) the detection of solar flare produced cosmic-ray particles are also presented.

INTRODUCTORY REMARKS

The subject matter of this Symposium is directed toward studies undertaken in the Antarctic during the past two years. In one respect what I have to report here does not rest upon observations in the Antarctic, but rather observations made on board vessels from the Antarctic expeditions as they cross the equator and approach or return from the Antarctic. Likewise the measurements which I report here do not pertain to and are not deeply concerned with the nature of the Antarctic as a region on the surface of the Earth. Rather, the studies are concerned with the geomagnetic field of the Earth which extends thousands of kilometers beyond the surface of the Earth, and the shape of the Earth's field extending from the equator toward the Arctic and the Antarctic. The discrepancies which we find in the description of this field have an important bearing upon Antarctic radio whistler and auroral studies as we shall later note.

During both the expeditions of the USS *Atka* (1954–1955) and the USS *Arneb* (1955–1956) we have had a semi-permanent laboratory containing special cosmic-ray apparatus in continuous operation from time of departure to time of arrival in the United States. The measurements on board the USS *Atka* have been made in cooperation with the National Research Council of Canada through the collaboration of D. C. Rose and J. Katzman. It was fortunate that special cosmic-ray apparatus was carried on board the HMCS *Labrador* into the Arctic the summer of 1954 and was transferred to the USS *Atka* prior to its departure to the Antarctic in December 1954. This made it possible for the first time to obtain an almost pole to pole series of observations of cosmic-ray intensity very near the time of solar minimum. The courses of the *Labrador* and the *Atka* are shown in Figure 1. The apparatus on the *Atka* was under the supervison of K. B. Fenton. The course of the USS *Arneb* and its 'round the world cruise is shown in Figure 2; the apparatus on the *Arneb* was supervised and operated by R. Vogt.

We shall now turn to a discussion of the scientific results derived from these two expeditions. Detailed accounts of the results and their implications have been published recently [*Simpson* and others, 1956 ab; *Rose* and others, 1956] and we shall draw upon these papers for our discussion here. Since the USS *Arneb* has recently returned to the United States, only a small portion of the results from this second expedition have so far been prepared.

THE GEOMAGNETIC FIELD EXTENDING INTO INTERPLANETARY SPACE

Ever since the work of Gilbert [*Gilbert*, 1893] in 1600, the study of geomagnetism has been directed mainly to the description of the permanent field of the Earth, the changes of the total field with time, and the origin of the field. We have detailed knowledge of the magnetic-field distribution over the surface of the Earth obtained from magnetic surveys. These data are analysed by introducing a magnetic-potential function which is expanded in spherical harmonics. The coefficients of the expansion are adjusted to give the best fit with the magnetic-survey data. The analysis shows that we may best describe the permanent field distribution by an equivalent magnetic dipole displaced from the center of the Earth and inclined to the axis of rotation. The magnetic-field distribution out to great distances from the Earth is, therefore, defined by these measurements provided we assume that the Earth lies in a non-conducting medium.

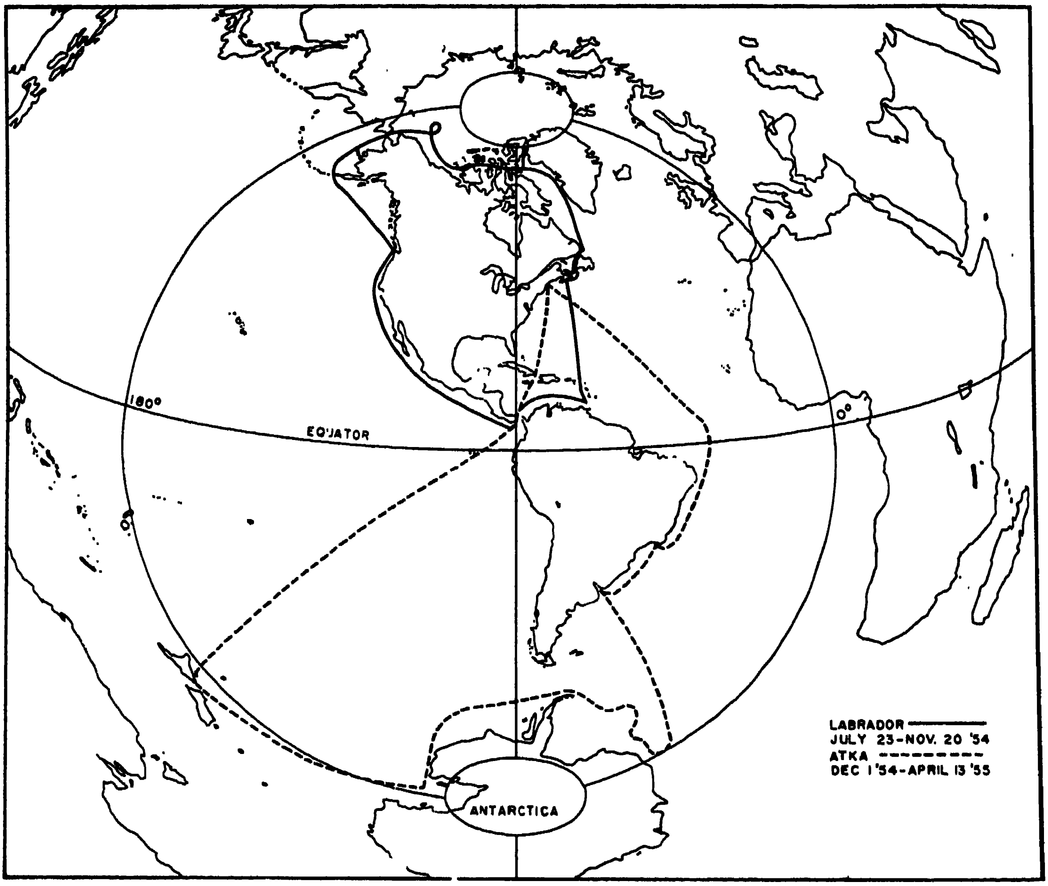

FIG. 1 – Routes of the icebreaker HMCS *Labrador* and the icebreaker USS *Atka*; both vessels carried the same neutron pile and vertical counter telescope

It is well known that external current systems (ionosphere, etc.) which produce additional contributions to the field at the surface of the Earth are not effective at large radial distances. Hence, our present-day assumptions regarding the magnetic-field distribution far beyond the surface of the Earth rest upon our knowledge of the surface fields and the extrapolation of the equivalent dipole field to large radial distances with the implicit assumption that there is no electromagnetic interaction between the rotating and inclined dipole field with the interplanetary medium.

Within the past few years we have learned from studies of zodiacal light [*Behr* and *Siedentopf*, 1953], radio whistlers [*Storey*, 1953], etc. that the electron density near the orbit of the Earth may be the order of 600 electrons/cm^3, in which case the conductivity of the medium is exceedingly large. We have also found relatively large discrepancies between the expected deflections of cosmic-ray particles and the observed deflections in the outer magnetic field. Thus, we raise here the questions: (1) What is the distribution of the permanent geomagnetic field in the nearby interplanetary medium? (2) How does it differ from the eccentric dipole model which has been developed over these many years from magnetic observations?

As the first step toward answering these fundamental questions we have at the Institute undertaken some simple experiments directed to the second of these questions. The role of the US Antarctic Expeditions in these experiments will soon become evident.

At present, we cannot directly measure magnetic fields beyond the altitude range of rockets or artificial satellites. Hence, we must be content with indirect observations on the influence of the geomagnetic field on charged particles of high energy, namely, cosmic rays. The theory for the motion of charged cosmic-ray particles moving in the main external field of the Earth has been explored extensively. Since at large distances the local anomalies in the magnetic field become negligible the interesting possibility arises that, without resorting

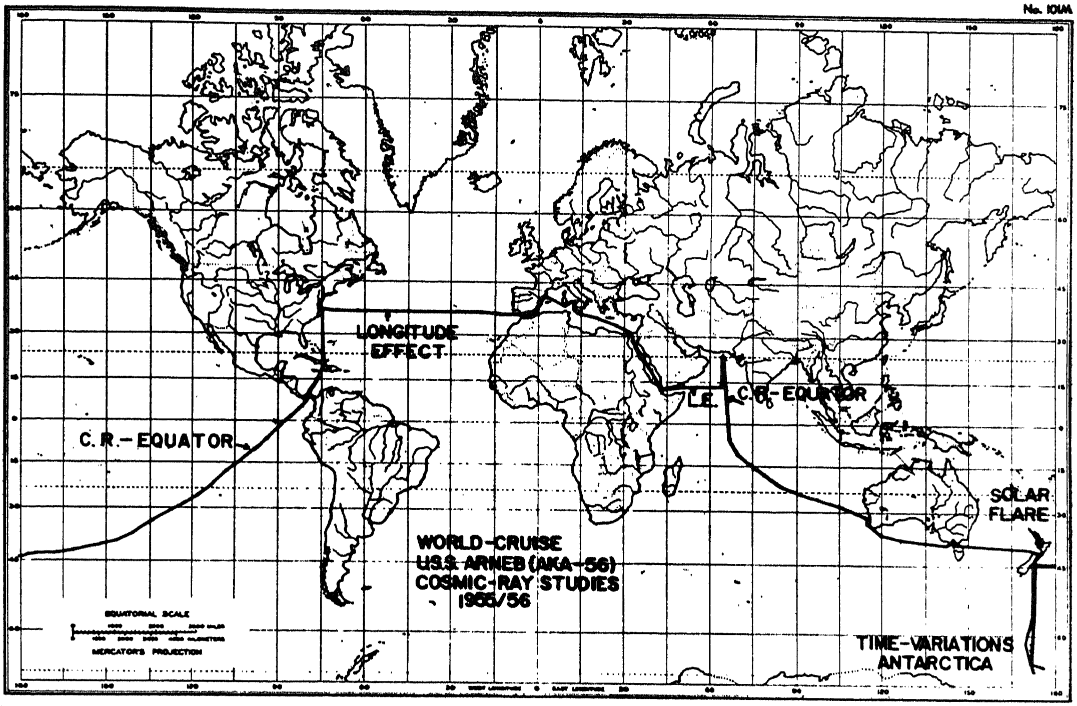

FIG. 2 – Route of the USS *Arneb* carrying a 12-counter neutron intensity monitor identical with the neutron monitors at Chicago and Climax, Colorado; upon return from Little America V the *Arneb* traveled westward from New Zealand to the United States

to surface magnetic fields, the orientation and magnetic center coordinates for the equivalent dipole moment of the Earth's magnetic field may be measured. More specifically, symmetrical properties of the geomagnetic field may be detected, as for example, the location of the geomagnetic equator. Thus, the incoming charged particles may be looked upon as 'probes' for exploration of the otherwise inaccessible magnetic fields around the Earth. The interesting question arises as to whether the description of the magnetic field required to account for the distribution of cosmic-ray particles arriving at the Earth is the same as the magnetic field described by the classical surface magnetic measurements.

For over 25 years the application of cosmic-ray observations to the description of the Earth's field has occasionally been discussed, but apparently anomalous results have led to the conclusion that the differences in distribution from the expected geomagnetic field were probably of meteorological origin, or due to local magnetic field anomalies. We have been interested in re-examining this problem since we now have the means for measuring cosmic-ray intensity which are strongly dependent on geomagnetic latitude, and are at the same time free from temperature effects in the atmosphere. This is particularly important since it is obvious that continuous cosmic-ray observations are required for a world-wide description of the field, and the investigator is limited to measuring deep within the atmosphere the secondary particles produced by the primary cosmic radiation (see Fig. 3). Irrespective of which component in the cosmic rays is being measured, the geomagnetic field produces two principle effects upon the total observed intensity: (1) It is minimum at the geomagnetic equator and increases as the observer moves toward either pole. This is the well-known latitude effect. (2) There is a longitude effect on cosmic-ray intensity which is most pronounced at the geomagnetic equator. The distance between the center of the geoid and the magnetic center is approximately 400 km, and the minimum energy which particles may have to reach the atmosphere is a function of their distance from this magnetic center (Fig. 4). Consequently, as an observer moves around the equator of the Earth in the atmosphere the cosmic-ray intensity varies with longitude of observation.

Conversely, if we know the position of minimum cosmic-ray intensity for all longitudes we may (a) define the plane of the geomagnetic equator for charged particles and obtain a measure of how perfect a plane the geomagnetic equator is, and

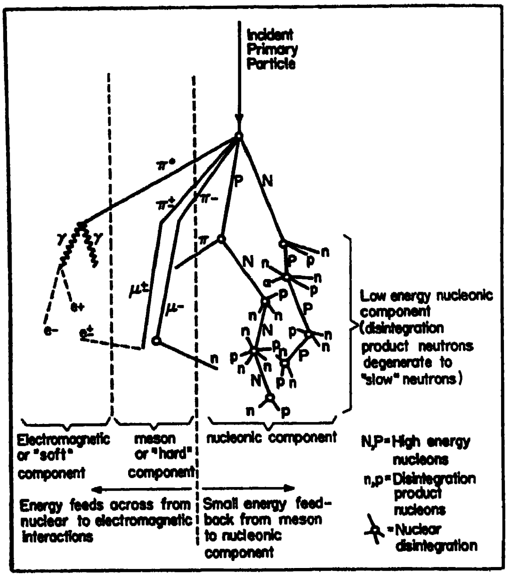
Incident Primary Particle
π^0
$\pi^\pm$
π^-
π
P
N
γ
γ
e+
e-
$e^\pm$
$\mu^\pm$
μ^-
n
p
a
Low energy nucleonic component (disintegration product neutrons degenerate to "slow" neutrons)
Electromagnetic or "soft" component
meson or "hard" component
nucleonic component
N,P=High energy nucleons
n,p=Disintegration product nucleons
=Nuclear disintegration
Energy feeds across from nuclear to electromagnetic interactions
Small energy feed-back from meson to nucleonic component

FIG. 3 – The production of secondary cosmic-ray particles and electromagnetic radiation following a collision with a primary particle and a nucleus in the atmosphere [*Simpson* and others, 1953]

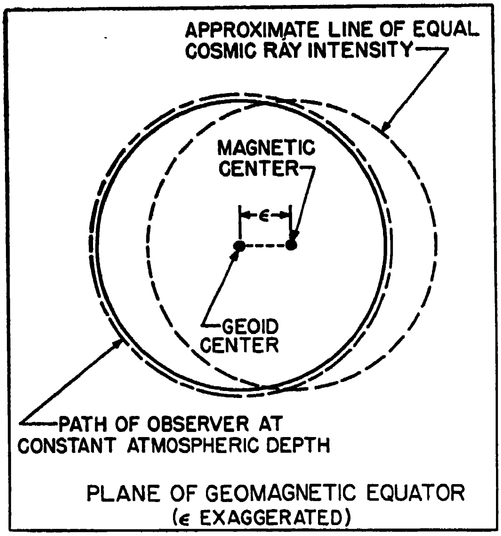
APPROXIMATE LINE OF EQUAL COSMIC RAY INTENSITY
MAGNETIC CENTER
ϵ
GEOID CENTER
PATH OF OBSERVER AT CONSTANT ATMOSPHERIC DEPTH
PLANE OF GEOMAGNETIC EQUATOR
(ϵ EXAGGERATED)

FIG 4. – The total cosmic-ray intensity along the path of the observer illustrates how the longitude-intensity dependence arises; the lowest intensity occurs near the longitude of closest approach to the magnetic center [*Simpson*, and others, 1956a]

(b) obtain a measure for the eccentricity of the magnetic dipole. Our first experiments have been directed to the former problem, namely the location of cosmic-ray intensity minima derived from the latitude curves around the Earth—we define the equatorial plane passing through these intensity minima as the cosmic-ray equator. This is the geomagnetic equator effective for cosmic-ray particles arriving from all directions in the sky.

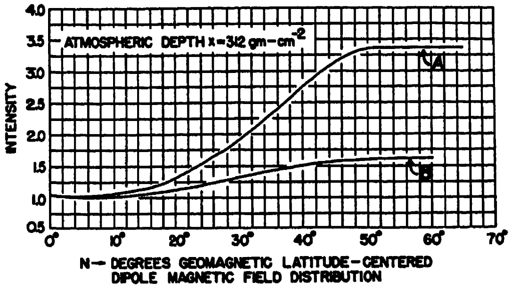

FIG. 5 – The latitude dependence of nucleonic component intensity (curve A) and meson intensity (curve B) for an atmospheric depth of $x = 300$ gm/cm^2; The development of these two components is illustrated in Figure 3 [*Simpson* and others, 1953]

Since the magnetic field interacts with incoming primary particles at great distances, and we are measuring the secondary particles produced by these primaries our first task is to relate observed secondary cosmic-ray intensity to the primaries, and the trajectories of these primary particles to the parameters of the external geomagnetic field.

The primary cosmic radiation is composed of approximately 85 pct protons, 14 pct alpha particles, and one per cent heavier nuclei, all stripped of their outer electrons. These charged particles experience deflections in a magnetic field which depend upon their charge and momentum. Particles undergo the same deflection in a magnetic field provided the quantity pc/Ze is the same for all the particles, where p is particle momentum, Ze the charge, and c the velocity of light. This quantity is called the magnetic rigidity N, measured in units 10^9 volts, i.e., Bv. By expressing the motion of particles in a geomagnetic field in terms of N, we describe the behavior of particles over the entire charge spectrum.

The primary radiation produces not only the meson compent but the nucleonic component as shown in Figure 3. The former possesses a very small latitude effect but the nucleonic component is strongly dependent upon magnetic latitude as shown in Figure 5. In addition, the nucleonic component is not influenced by temperature effects within the atmosphere. Thus, for the measurements of the nucleonic component deep within the atmosphere of the Earth, we are concerned with the primary radiation producing the secondary nucleonic component which reaches the detector.

Over the past few years we have developed methods for detecting this nucleonic component by means of the local production of neutrons within a pile-like structure composed of lead and paraffin. A description of the instrumentation has been published [*Simpson* and others, 1953]. From our knowledge of the neutron intensity and the changes of neutron intensity within this pile we are able to deduce the changes of primary intensity at the top of the atmosphere. More precisely, we observe the counting rate of nucleonic component particles within the detector at atmospheric depth × grams/cm², arising from the integral cosmic-ray intensity of all particles arriving near, or from, the vertical. We call R the counting rate for primaries arriving from the vertical. If we define the differential primary particle intensity

$$j_z = \frac{C_z}{\left[\dfrac{pc}{Ze}\right]^{2.5}} = \frac{C_z}{N^{2.5}}$$

for particles of charge Ze, we may then write an expression for the observed counting rate within the neutron pile

$$R(\varphi, \lambda, x, t) = \sum_z \int_{N_c(\varphi,\lambda)}^{\infty} S(N, x) j_z(N, t)\, dN$$

where S is defined as the average specific-yield function of secondary nucleonic component particles per incoming primary particles $Z = 1$ or $Z = 2$, since we neglect the effect of heavier nuclei. We see that R depends upon magnetic rigidity. From Stoermer theory we note that whether or not a particle of given magnetic rigidity can arrive at the top of the atmosphere depends upon the magnetic longitude φ and magnetic latitude λ. Hence we see that the counting rate depends upon both magnetic longitude and magnetic latitude for any given atmospheric depth and time of measurement t. The integration is carried over the primary spectrum from the highest particle rigidities down to the minimum rigidity which a particle may possess and yet reach the atmosphere near the vertical. This critical cut-off rigidity is defined as N_c. N_c is a function of geomagnetic field parameters, and it is through this functional relationship that we obtain our information on the symmetry properties of the geomagnetic field of the Earth using nucleonic component detectors. Details on the theory and method of measurement for relating cosmic-ray intensity observations to the coordinates of the geomagnetic equator and for measuring the eccentricity of the magnetic dipole have recently been discussed [*Simpson* and others, 1956ab].

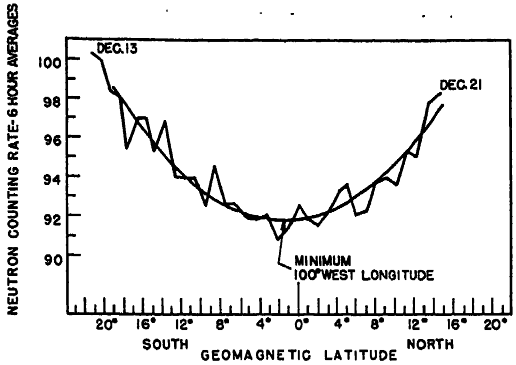

Fig. 6. – Sea-level neutron intensity measured December, 1954 near the geomagnetic equator; the smooth curve is the least-squares fit of a parabola to 36 points from the data [*Simpson* and others, 1956a]

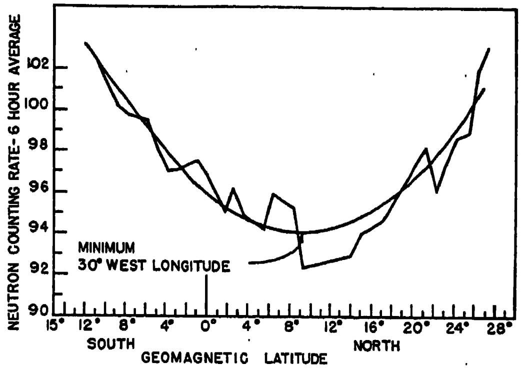

Fig 7 – Sea-level neutron intensity measured March–April 1955 near the geomagnetic equator [*Simpson* and others, 1956a]

Since in this paper we shall only consider the location of the effective geomagnetic equatorial plane for cosmic-ray observations, we shall first discuss the measurements obtained during the Antarctic Expeditions which cross the geomagnetic equator in passing from the United States to the Antarctic and return. Neutron intensity monitors were carried on board the USS *Atka* in a semi-permanent structure during 1954–1955, and on board the USS *Arneb* in 1955–1956. The USS *Atka* crossed the equator at 30° W and 100° W longitude. The USS *Arneb* crossed the equator at 100° W longitude and 65° E longitude. Complete details of the instrumentation, pressure correction, and two hemisphere sea-level latitude curves have been published elsewhere [*Rose* and others, 1956]. In addition, neutron-intensity observations in aircraft at 78° W longitude have been available since 1948, and, in fact, gave the first clue that there was a severe and real discrepancy between cosmic-ray observations and magnetic-field observations [*Simpson*, 1951]. The results for the USS *Atka* crossing the equator at 100° W and 30° W longitude are shown in Figures 6 and 7.

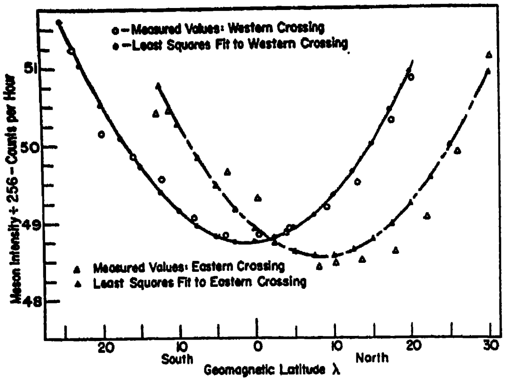

FIG. 8 – Sea-level meson intensity measured with triple coincidence detectors at the same time as the neutron measurements shown in Figures 6 and 7 [*Simpson* and others, 1956a]

TABLE 1—*Location of minimum cosmic-ray intensity; the difference between the positions of the geomagnetic equator and the effective cosmic-ray equator is* Δλ, *with* +Δλ *placing the cosmic-ray equator north of the geomagnetic equator.*

Reference	Longitude	Δλ	Date
Clay [1934, p. 369][a]	3° W	+4°	1933
USS *Atka* [*Simpson* and others, 1956a]	30° W	+9°	1955
Simpson [1951]	77° W	+4°	1948
Johnson and *Read* [1937, p. 557]	80° W	+5°	1935
USS *Atka* [*Simpson* and others, 1956a]	100° W	−1°	1954
Compton and *Turner* [1937, p. 779]	170° W	−4°	1936
Law, McKenzie, and *Rathgeber* [1949, p. 493]	145° E	−6°	1948
Sekido, Asano, and *Masuda* [1943, p. 439]	121° E	−3°	1937
USS *Arneb*	65° E	+2°	1956

[a] This point is somewhat uncertain.

The meson intensity from the vertical was also measured with a three-fold vertical-counter telescope located in the same cabin as the neutron pile on board the USS *Atka*. The absorber was 12.5 cm of lead. The data were corrected for pressure but not for the changes in atmospheric temperature with the results shown in Figure 8. It is clear from these two sets of observations that the positions of the minima are in agreement with the nucleonic component measurements even though the intensity minima are less well defined because of the small latitude dependence of the meson intensity. Consequently, we conclude that even for charged-particle detectors the upper atmosphere temperature distributions do not conceal the positions of the minima.

Hence, with the conclusion that the meterological and primary intensity variations do not account for the major discrepancies in location of the minima with respect to the geomagnetic equator as shown in Figures 6, 7 and 8, we have reexamined the ion chamber and counter telescope observations which have been published throughout the literature since 1933. We used these data to locate additional minima, and we have given the deviations Δλ of these cosmic-ray intensity minima from the expected geomagnetic dipole equator in Table 1. The errors in the charged-particle data are larger than for the neutron-intensity observations, and since they are influenced by atmospheric-temperature effects, we have weighted the neutron measurements more heavily than the charged-particle measurements. The positions of these minima have been plotted on a curve (Fig. 9) from which it is seen that there is a large and significant discrepancy between the location of the geomagnetic equator derived from surface field measurements and the equatorial minima from the cosmic ray-intensity observations.

If we assume that the cosmic-ray data prescribe an equatorial plane for the external magnetic field of an eccentric or distorted dipole then they should define an almost perfect sine curve when plotted on geographic coordinates. We have fitted a sine curve by the method of least squares under two different assumptions: In one case we fitted a sine curve to the data assuming that the amplitude is the same as that given by the geomagnetic field data and have adjusted the phase of the curve. For the second curve, we have fitted both the amplitude and phase of the sine curve to the data. These results imply that the location of the dipole magnetic-moment vector required to satisfy the deflection of cosmic-ray particles could be rotated westward 40–45° without necessarily changing its inclination or eccentricity. This is in disagreement with the established position of the dipole based upon surface field measurements, and we shall return to this discrepancy later in our discussion.

If our results define an effective geomagnetic equator for charged particles approaching the Earth from great distances in the field of an eccentric or distorted dipole then the world-wide geomagnetic coordinates to be used in explaining cosmic-ray effects will be different than those in current use. Upon looking into this matter we find, indeed, that this is the case. Large discrepancies in the measured fluxes of cosmic-ray particles between Europe and the United States are removed by the assumption that the effective geomagnetic equator represents roughly a new set

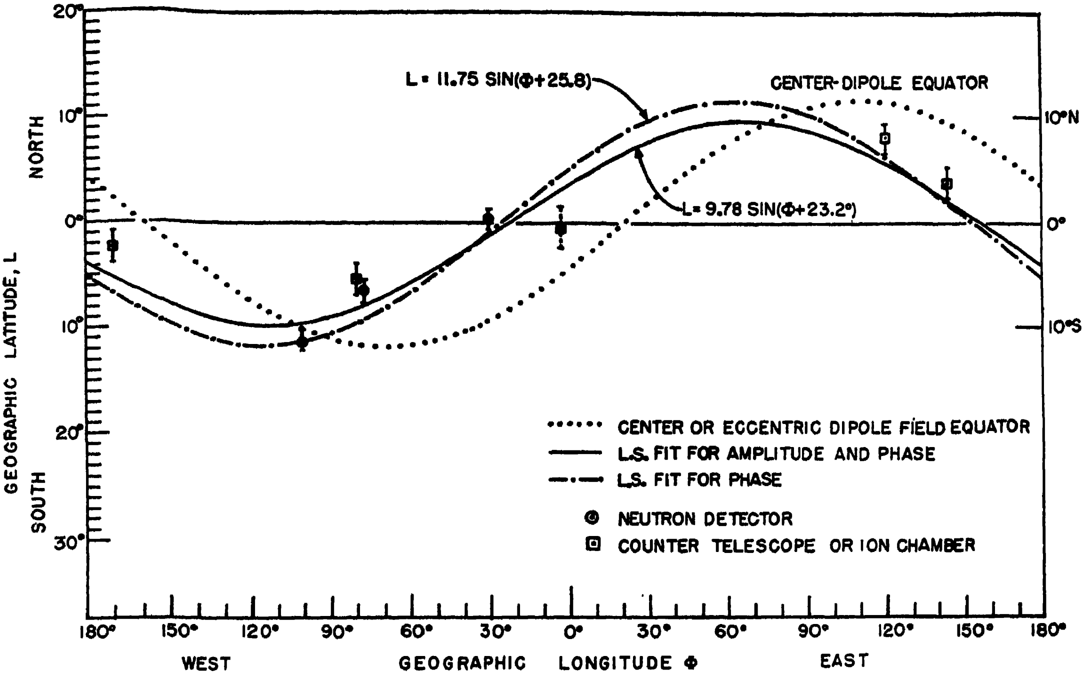

FIG. 9 — The geographic coordinates for the minima of cosmic-ray intensity are shown both for neutron and meson intensity data; the presently accepted position of the geomagnetic equator for both magnetic and cosmic-ray studies is shown as a dotted line curve; the effective cosmic-ray equator derived from measurements is shown as the broken, or the solid line; the inclined equatorial plane appears to be shifted *westward* approximately 40–45° [*Simpson* and others, 1956a]

of coordinates extending at least to intermediate north and south latitudes. These and other anomalies have been discussed elsewhere [*Simpson* and others, 1956ab].

If we assume that the discrepancy between the effective cosmic-ray equator and the geomagnetic equator described in Figure 9 arises from the Earth's permanent magnetic field, then the discrepancy can only be taken into account by changing the gauss coefficients already well established from the dipole term of the potential function. This leads to disagreement with the known surface magnetic-field distribution. On the other hand, it is clear from the large scale of the effect on high energy charged particles that the Earth's main field extending far from the surface of the Earth is involved in this problem. Consequently we are led to a tentative interpretation of this phenomenon which requires that the outer magnetic-field distribution converge to the already established magnetic-field distribution at the Earth's surface.

We interpret our measurements as evidence that the magnetic field of the Earth is immersed in a highly conducting interplanetary medium, and, because of the rotation of the inclined dipole, the outer magnetic field interacts with the ionized medium in such a way that the field is greatly distorted from the classical configuration expected from magnetostatics. We do not yet know the extent to which ionized gas is carried by the rotating and tilted geomagnetic field, nor the magnitude of the 'drag effect' which the ionized medium exerts upon the field even farther from the Earth. In any case, a westward shift of the effective equatorial fields might be expected from the counter clockwise rotation of the Earth. The dynamics of this outer region are not understood at present; only recently has there been serious consideration given to the astrophysical problem of a rotating and magnetized body immersed in a highly conducting medium [*Lüst* and *Schlüter*, 1954].

We cannot conclude from the effective geomagnetic equator coordinates for cosmic rays that these changes in coordinates may be extrapolated uniformly over the entire Earth. On the contrary, the Arctic and Antarctic cosmic-ray data provide tentative evidence that such an extrapolation would be a poor approximation for high magnetic latitudes [*Rose* and others, 1956]. But more work remains to be done on this latter question since

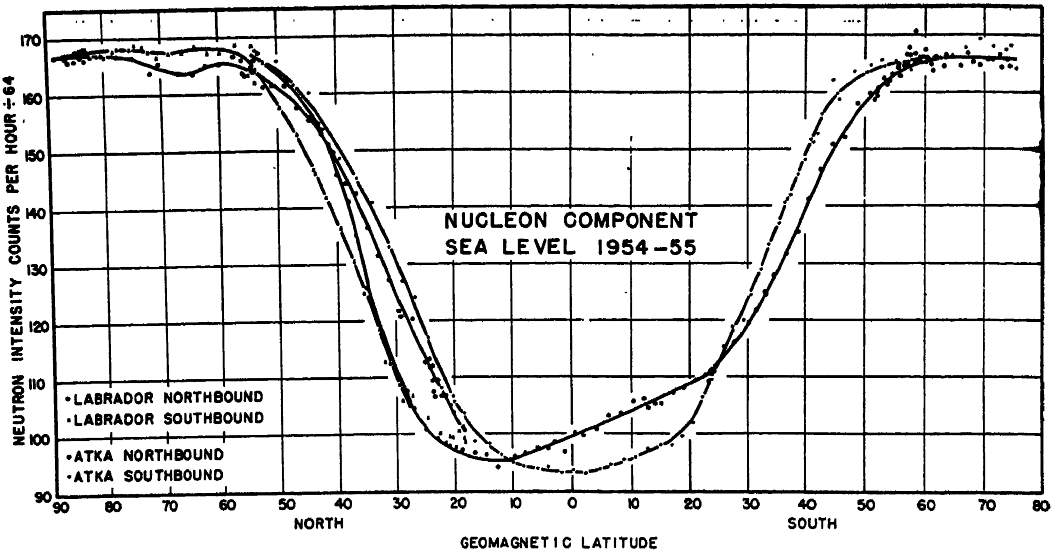

FIG. 10 — The sea-level nucleonic component intensity corrected for intensity variations with time; the geomagnetic longitude effect produces considerable distortion [*Rose* and others, 1956]

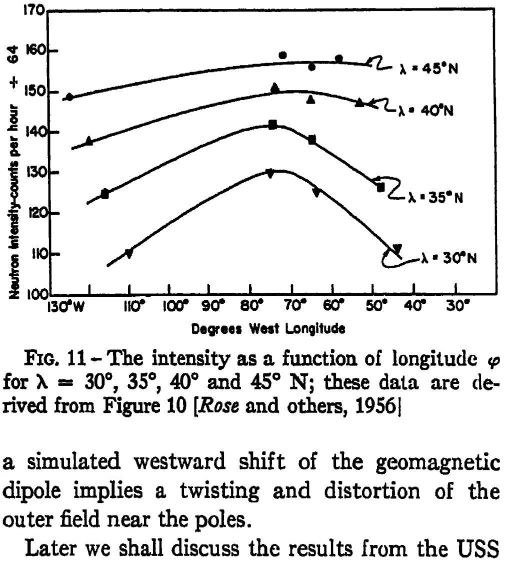

FIG. 11 - The intensity as a function of longitude φ for λ = 30°, 35°, 40° and 45° N; these data are derived from Figure 10 [*Rose* and others, 1956]

a simulated westward shift of the geomagnetic dipole implies a twisting and distortion of the outer field near the poles.

Later we shall discuss the results from the USS *Arneb* during the 1955–1956 Antarctic Expedition which confirms the position of the cosmic-ray equator.

WESTWARD SHIFT OF ECCENTRICITY FOR THE EFFECTIVE GEOMAGNETIC DIPOLE

In Figure 10 we have shown the latitude curves of cosmic-ray intensity extending from the Arctic into the Antarctic. These are the combined data from the *Labrador* and the *Atka* expeditions. At a given geomagnetic latitude we may determine the relative neutron intensity as a function of longitude as shown in Figure 11. From our earlier discussion it was clear that the longitude effect around a circle of constant geomagnetic latitude should show both a maximum and a minimum cosmic ray intensity, with the maximum occurring near the meridian plane on the far side of the geoid as indicated in Figure 4. Geomagnetic theory predicts that the cosmic-ray intensity maximum should be near 20° W longitude. However, from Figure 11 we see that measurements place this maximum near 60°–70° W longitude. It is interesting to note that the longitude effect in general shows approximately the same westward shift that is found for the cosmic-ray equator, namely about 40°. We wish to mention here that the explanation to account for the longitude shift proposed by *Lemaitre* [1937] namely a parallactic effect on the cosmic ray particle trajectories cannot account for the magnitude of this observed shift in longitude.

THE KNEE OF THE LATITUDE CURVES IN THE SOUTHERN HEMISPHERE

During the cruise of the USS *Atka* there was an opportunity for the first time to explore the most southern extent of the change in nucleonic-component intensity with geomagnetic latitude. This represents the geomagnetic cut off latitude at which particles in the range 1-2 Bev are no longer able to propagate their secondary radiation down to sea level. The results are shown in Figure 12. The longitude effect at 180° and 5–45° W is also shown for the southern hemisphere.

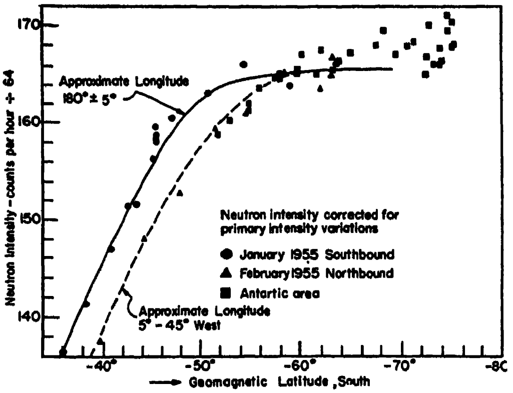

FIG. 12 — The portion of the latitude curve produced by low energy primaries; the curve levels off at a geomagnetic particle cut off of ~ 1–2 Bev for primary protons [*Rose* and others, 1956]

PRELIMINARY RESULTS FROM THE 1955–56 ANTARCTIC EXPEDITION

The cosmic-ray equator—The location of the equator at 100° W was in agreement with the results from the USS *Atka*. A new point at an entirely different longitude was chosen to test critically the properties of the effective geomagnetic equator; 65° E was selected to determine the maximum amplitude and, hence, the tilt of the field axis. It was also chosen as a test of the assumption that a sine curve is a reasonable representation of the cosmic-ray-minima positions. The results show that the point for 65° W lies 2° north of the classical geomagnetic equator and between the two curves drawn to represent the effective cosmic-ray equator in Figure 9. This is strong supporting evidence that the cosmic-ray equator exists and has the general form shown in Figure 9.

The solar flare of February 23, 1956—On its return from the Antarctic the USS *Arneb* was in the harbor of Wellington, New Zealand, at the time of the large solar flare of February 23, 1956. A sharp and dramatic increase of cosmic-ray intensity occurred as shown in Figure 13. The laboratory on board the USS *Arneb* was equipped with special electronic equipment to record the sharp increase in intensity in one minute intervals. This observation at Wellington was of unusual importance for our studies at Chicago since it enabled us for the first time to study simultaneously the arrival of solar-produced cosmic rays in two hemispheres using neutron detectors. The results show that the low-energy particles arrived at Chicago and Wellington simultaneously within the error of measurements, ± one minute. The study of the entire cosmic-ray event and the role which the data from the USS *Arneb* played in the conclusions is being published [*Meyer* and others, in press].

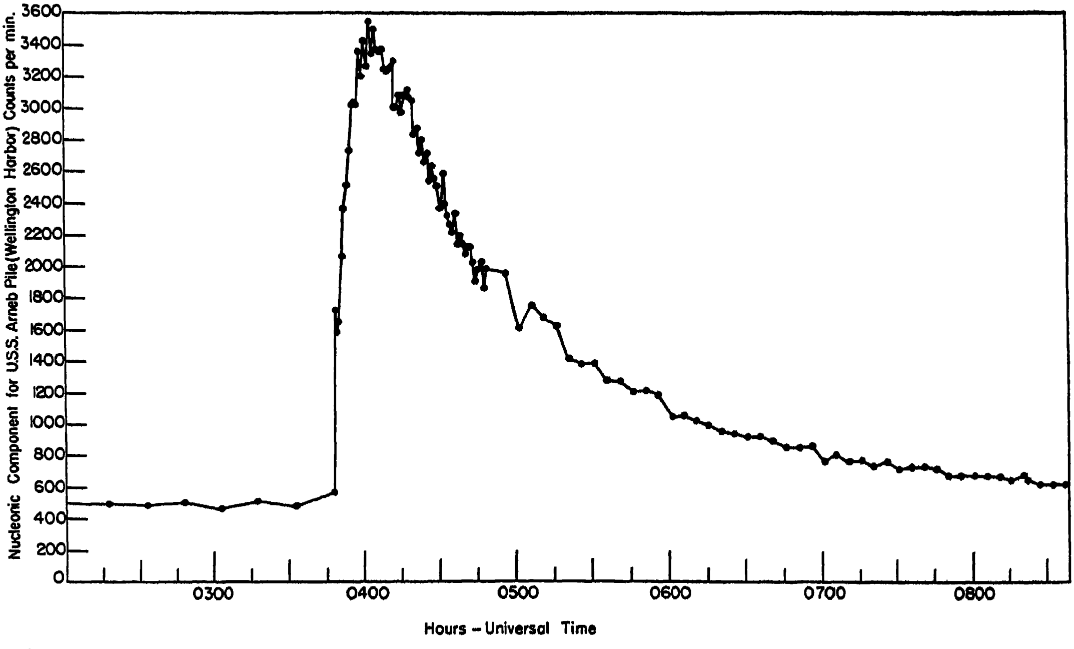

FIG. 13 — The temporary increase of cosmic-ray intensity associated with the solar flare of February 23, 1956; this represents the arrival of particles produced in the vicinity of the Sun; this event was recorded while the USS *Arneb* was anchored in the harbor of Wellington, New Zealand [*Meyer* and others, in press].

Concluding Remarks

We may conclude from these simple observations that there is a field of research opening for the exploration of the outer magnetic field by cosmic-ray observations. At the present time we have restricted ourselves principally to the geomagnetic equator because this we can more simply understand with the limited data available. It is however very important that observations of this type be carried to both the Arctic and Antarctic over a wide range of longitudes in order to explore fully the nature of the outer geomagnetic field and its interaction with the interplanetary medium. The scope and size of such an undertaking is beyond that of university investigators, and hence, we hope that larger organizations, principally government groups, will find it possible to undertake during the International Geophysical Year many of these measurements which seem almost certain to yield interesting and fundamental results.

None of this work would be possible without the excellent support from the U. S. National Committee for the International Geophysical Year, Hugh Odishaw, and his administrative staff. Likewise, the National Committee and our research group have received strong and continuing support from both the US Air Force and US Navy. In particular we wish to thank the officers and crew of the USS *Atka* and the officers and crew of the USS *Arneb* for their assistance in making these continuous observations, and for assistance in seeing that the laboratory was kept in operation. We are especially grateful to Admiral George Dufek and his officers for the support which they gave in arranging the trip of the USS *Arneb* around the world following its mission in Little America V.

In particular I wish to thank K. B. Fenton, who so ably handled the apparatus on the USS *Atka* and Rochus Vogt, who supervised the installation and made all of the observations on board the USS *Arneb*, for their cooperation and support in obtaining and preparing the data for these two expeditions. I wish also to thank the National Research Council of Canada and D. C. Rose and J. Katzman for their active cooperation, and their arrangements for transferring apparatus from HMS *Labrador* to the USS *Atka* making possible the first pole to pole studies of cosmic-ray intensity.

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Antarctic Fauna and Some of its Problems

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Abstract—Distribution of birds, mammals, fishes, and other forms of animal life common to the Antarctic region are discussed briefly. These include the emperor and Adelie penguins, and the south polar skua, which species are considered indigenous to the area. Other bird species which either nest or spend considerable time in the region are mentioned. The four pinnipedia considered endemic to the Antarctic zone are the Ross, crabeater, Weddell, and leopard seals, and their habits are cited. Occurrence of marine invertebrates and fishes is shown by phyla, class, or order. Terrestrial fauna consists primarily of arthropods. References are made to some of the past zoological studies, and the inadequacies of our present knowledge of Antarctic animals are considered. A zoological program which might be coordinated with geophysical studies is suggested. This includes collecting, bird banding, seal marking, life-history habits, population dynamics, food habits, seasonal movements, physiological studies, and location of the breeding grounds of the Ross and crabeater seals. The value of paleontological studies is discussed.

The International Geophysical Year (IGY) offers unprecedented opportunity to carry out much-needed zoological studies in the Antarctic on a scale never before possible. At the same time, it is realized that zoology is a 'periphery' science in this case, and any work conducted must be subordinate to the geophysical research. In this paper the distribution of fauna in the Antarctic will be reviewed briefly; some of the past research carried out will be discussed, and a program of zoological studies which can be correlated with the geophysical work will be proposed.

DISTRIBUTION OF FAUNA

Birds—Bird life of Antarctica is essentially marine, and in keeping with general characteristics of the biota of cold oceans, is poor in number of species but relatively rich in individuals. Land birds are found only in the sub-Antarctic zone. Antarctic avifauna may be generally divided into those species inhabiting the islands in the sub-Antarctic, and those found on islands within the Antarctic Circle and along the Continent. Since opportunity for detailed studies lies primarily with species found in the vicinity of the proposed American bases in the latter zone, this paper will be confined to birds considered typical of that area. This region falls well within that area having the warmest-month isotherm of 32° F [Gould, 1940].

Within the Antarctic the Emperor Penguin (*Aptenodytes forsteri*), the Adelie Penguin (*Pygoscelis adeliae*), and the South Polar Skua (*Catharacta skua maccormicki*) are circumpolar in distribution, and might be considered truly indigenous to the area. The Emperor Penguin, following the end of its winter breeding season, spends the summer no further north than the edge of the pack ice. Conversely, the Adelie Penguin nests on the islands and mainland of the Continent during the summer, and spends the winter within the pack ice. The South Polar Skua has the distinction of being the world's most southerly avian traveler. Scott saw it in January, 1912, at latitude 87°20′ S, longitude 160° 40′ E, 160 miles from the south pole, and a sledging party on the second Byrd Expedition reported seeing this bird at latitude 86° 05′ S [*Siple* and *Lindsey*, 1937].

Murphy [1936] says that the Emperor Penguin is the most truly Antarctic of all birds, and the Adelie the most thoroughly investigated of penguins. His classic publication on these and other south-polar species should be reviewed by anyone contemplating research on birds in this region.

A considerable number of additional bird species either nest on the islands and coasts of Antarctica or spend much of their time within this zone, and can be considered circumpolar in distribution. These include the Giant Fulmar (*Macronectes giganteus*); Silver-gray Fulmar (*Priocella antarctica*), which except for the Snow Petrel is the commonest bird in the pack ice throughout the whole circumpolar belt; Cape Pigeon (*Daption capensis*); Snow Petrel (*Pagodroma nivea*), which is seldom found away from the pack ice except during breeding seasons; Antarctic Petrel (*Thalassoica antarctica*); Antarctic Wilson's Petrel (*Oceanites oceanicus exasperatus*); Antarctic Whale-bird (*Pachyptila desolata*); Antarctic Tern (*Sterna vittata*); Antarctic Blue-eyed Shag (*Phalacrocorax atriceps bransfieldensis*); and the Kelp Gull (*Larus dominicanus*). Other species will, of course, come within the zone at times, but according to *Gain* [1914], only about 32 species of birds penetrate beyond latitude 60° S and most of these are sub-Antarctic rather than polar wanderers.

Mammals—Although the Antarctic seas are rich in marine mammals, particularly seals and whales, whaling constitutes the only industry in the whole Antarctic region. Research on whales is possible only through cooperation of the industry which is now being effected through action of the International Whaling Commission. Invaluable biological investigations have been conducted by the Marine Biological Station at South Georgia Island, and by the British Research ships *Discovery*, *Discovery II*, and *William Scoresby*, under supervision of the Discovery Committee, now the National Institute of Oceanography, of the British Colonial Office [*United States Navy Department*, 1943]. The Norwegian Whalers Association has also carried out valuable research with the *Norvegia* and the *J. H. Bull*. British and Norwegian whaling companies, together with the Commission, have recently financed whale marking in the Antarctic, which was carried out aboard the *Enern* [*Polar Record*, 1956].

Worthwhile studies of Cetaceans, other than observations on species distribution and abundance enroute to and in the vicinity of some of the bases, would be generally impossible during International Geophysical Year, so this group of animals will not be given further consideration.

Whereas mammal life in the Arctic is closely related to forms found within the adjacent temperate belt, much of the similar life in the Antarctic is largely endemic. This distinctive character is exemplified in the four well-marked genera of truly Antarctic seals, which are unusual in that they show remarkably diverse structure correlated with no less distinct habits [*Barrett-Hamilton*, 1901].

The Crabeater Seal (*Lobodon carcinophagus*) lives in the pack ice during winter and summer, is circumpolar in the Antarctic, but occasionally reaches sub-Antarctic latitudes. It appears to be semi-migratory, is gregarious, and occurs in relatively great numbers. It lives almost exclusively on the pelagic shrimp, *Euphausia superba.*

The Weddell Seal (*Leptonychotes weddelli*) is more southern in distribution than the Crabeater Seal, and its range is confined more to the fast-ice along the coasts throughout the year. It is gregarious, occurs in considerable numbers in parts of its range, is circumpolar, and occasionally reaches sub-Antarctic latitudes. It feeds on fish and Cephalopods.

The circumpolar Ross Seal (*Ommatophoca rossi*) is the rarest of the four polar species. It inhabits the pack-ice belt, is solitary in its habits, and appears to confine itself to the southerly parts of the area, being unknown to the northward of the pack ice. Its diet is probably fish and Cephalopods.

The Leopard Seal (*Hydrurga leptonyx*) has a rather broad latitudinal range, and is found from the shores of the Antarctic Continent northward to parts of the temperate zone. It is semimigratory, solitary in its habits, and is relatively widespread, but scarce. This aggressive seal preys on other seals and penguins, as well as on fish and Cephalopods.

Marine zoology—A considerable amount is known about the richness of plankton in Antarctic waters, with the resultant high productivity of marine invertebrates and vertebrates. These waters are perhaps the most productive in the world as a result of continuous upwelling of replacement water bringing plant nutrients such as phosphates and nitrates. Furthermore, the shelf fauna for both species and genera is more independent than any other fauna of approximately the same regional dimensions. Besides seals and whales, in these seas are found representatives of practically all the various invertebrate groups. One of the most important of invertebrates is the 'red krill,' *Euphausia superba,* whose food consists of plankton. This shrimp is a most important food for great numbers of vertebrates, particularly whales.

Fishes native to waters in the Antarctic zone were assigned by *Regan* [1914] to two districts, Glacial and peri-Glacial. He defined the Antarctic as that zone southward of the mean annual surface isotherm of 6° C, which some consider as an unsatisfactory zonal boundary [*Lindsey*, 1940, p. 463]. *Ekman* [1953, pp. 220–222] indicates the temperature limit for Antarctic marine fauna lies about 4 to 5° C. In Regan's Glacial district, which is the region adjacent to most of the proposed polar bases, 90 pct of the fishes are Nototheniiformes, a Percoid group confined to waters of the far south. This group is somewhat analogous to the cod in the northern hemisphere. Other fishes of this district include eelpouts (*Zoarcidae*), many species of which are circumpolar. According to *Ekman* [1953, pp. 220–222] the Antarctic fish fauna contains 90 pct endemic species and 65 pct endemic genera.

Terrestrial and fresh-water fauna—The terrestrial and fresh-water fauna in the Antarctic is comprised primarily of primitive forms of Arthropods, which are usually found among mosses and lichens, or in moist places or fresh-water pools. These include large numbers of the dipterous genus *Podurellae;*

a wingless Chironomid; a wingless mosquito; and Collembola, of which there are at least 11 species representing nine genera in the Antarctic land province. According to *Enderlein* [1909], the only widely distributed species of insects in the Antarctic are parasites of seals.

Other animal life includes microscopic mites, about 16 species of Tardigrades or water bears, and a similar number of species of fresh-water Rotifers [*Lindsey*, 1940, p. 462].

SUGGESTED RESEARCH

Birds—Ultimate understanding of the distribution of birds in the circumpolar Antarctic oceanic area is dependent upon far more extensive collections than now exist, together with banding. This should be followed by broad taxonomic work such as only satisfactory collections can make possible. No adequate series of Antarctic specimens, representing forms from an entire breeding range of a single species have yet been brought together, and it is doubtful whether a single museum in the world possesses an even moderately good representation of Antarctic birds as a whole [*Murphy*, 1928]. Polar bases maintained during the IGY offer a rare opportunity to accomplish this.

In addition to collecting, the IGY program offers an unprecedented chance to carry out extensive work in bird banding to determine distribution and migrations. It is proposed that a widespread, international cooperative banding program be carried out at polar bases to be maintained by all the countries. This would include the South Pole Station, where the South Polar Skua may prove to occur regularly during the summer. To accomplish this it is suggested that the Fish and Wildlife Service of the U. S. Department of the Interior provide bands and act as a central organization to which returns should be made. This Service is well-equipped to carry out such work on an international scale. In addition to regular bands, provision should be made for use of colored markers which would make field identification possible.

Little is known of the Antarctic Continent as an original center of dispersal for some bird groups. We might infer that penguins are of Antarctic or at least Austral origin, and there is paleontological support of this from fossil remains taken by the Swedish Expedition at Seymour Island in West Antarctica [*Wiman*, 1905]. Penguin fossils collected comprise not fewer than six forms which have been generically distinguished. These, together with four or five Patagonian middle or late Tertiary species and two New Zealand species bring the known number of extinct penguins to twelve or more. Such fossil collections suggest that penguins may have evolved from a tribe of terrestrial birds which were inhabitants of the Antarctic Continent during the long period of mild climate indicated by fossil vegetation. Evaluation of this theory is possible through further paleontological discovery, and through morphological studies.

The Emperor Penguin provides one of the most interesting fields for research. *Wilson* [1907] discovered the first rookery of this species at Cape Crozier in 1902. Nothing further was known of the life-history habits of this winter-breeding bird until the Falkland Islands Dependencies Survey discovered a rookery on Dion Islets off the coast of Palmer Land (Graham Land) in Marguerite Bay, south of Adelaide Island, in 1948. Its breeding behavior and development were described in an excellent publication by *Stonehouse* [1953]. The embryology of the species was discussed by *Glenister* [1954]. The German South Polar Expedition of 1901–03 had previously reported the presence of a rookery near Gaussberg in King Wilhelm II Land [*Vanhoffen*, 1905]. Another rookery was reported by *Mawson* [1915] at Haswell Island, near Gaussberg. No studies were carried out at these two latter areas, however. Both the Cape Crozier and Haswell Island rookeries were established on sea ice, and apparently the Gaussberg rookery, which was never actually visited, was similarly located. The French Polar Expedition to Adelie Land in 1949–51 also discovered an Emperor Penguin rookery at Pointe Geologie, and life-history habits were observed by *Sapin-Jaloustre* [1952], *Cendron* [1952], and others. The Adelie Penguin was also studied here [*Sapin-Jaloustre* and *Bourliere*, 1952]. The most recent rookery was discovered by members of the 1954–55 Australian National Antarctic Research Expedition at Taylor Glacier in about longitude 60° 58′ E, on MacRobertson Coast [*Polar Record*, 1955].

These are the known rookeries of the Emperor (see Fig. 1), although large groups of adults were observed by members of the 1949–52 Norwegian-British-Swedish Expedition at Norsel Bay (latitude 71° 03′ S, longitude 10° 56′ W), as well as in the pack ice of the Weddell Sea (Ove Wilson, personal correspondence, 1956). While no rookery was found, two juvenile birds which had just finished moulting were observed, so there is little doubt that the species breeds in this area. Young birds were observed off Caird's Coast, in this same region, by Shackleton's 1914–16 Expedition [*Falla*, 1952].

Additional life-history studies of the Emperor Penguin which, incidently, exhibits no territorial-

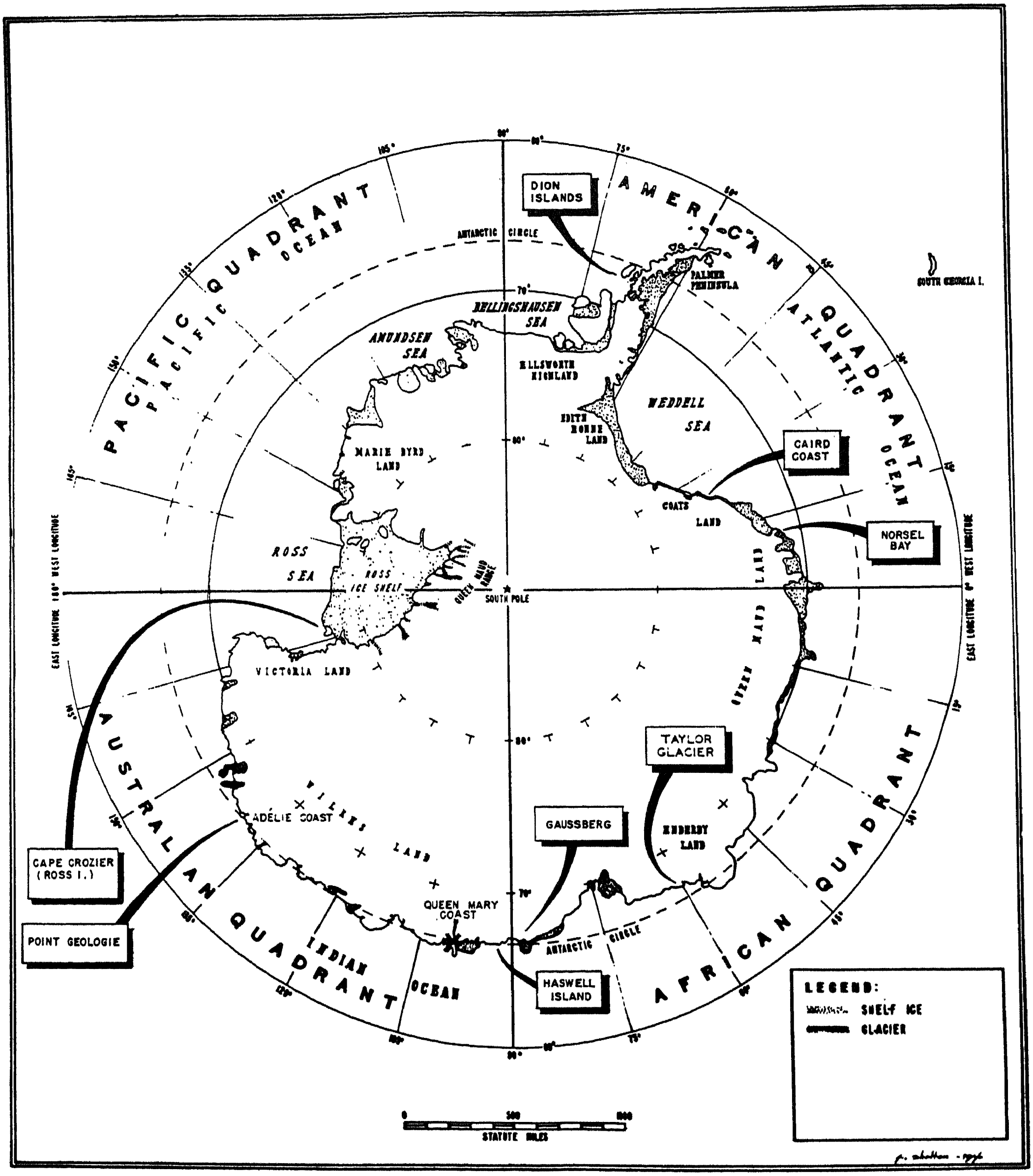

FIG. 1 – Emperor Penguin rookeries in Antarctica

ism during nesting, should be carried out. New rookeries could probably be located near some of the bases. It would be of value to obtain data on the social organization of not only the Emperor but also the Adelie Penguin breeding colonies. These birds are highly peculiar in many ways, and their social life, especially the communal care of the young, is of great interest and needs further detailed study.

As reported by *Friedmann* [1945], collections of Antarctic Wilson's Petrel are rather rare, and more of this sub-species, together with the Antarctic Blue-eyed Shag, should be taken at the various bases to further clarify the classification as well as the distribution.

Diving habits of penguins, as well as seals, offer an interesting subject for research. This might readily be accomplished, in part, through use of a capillary-tube manometer for determining water pressure.

There is evidence to show that the proportion of white Giant Fulmars, in relation to the normal dark-plumaged birds, increases with latitude, and observations should be made of such plumage phases.

The above suggested problems provide a large field for research on birds such as few other areas can offer. From even a cursory review of the literature one constantly finds such statements as, "I find no description of the downy young of the Silver-gray Fulmar....Neither the eggs nor the downy young of the Antarctic Petrel appear to have yet been described in literature....Our knowledge of even the best-known species of Storm Petrels is no more than casual and fragmentary, and there is a great dearth of objective description concerning just what takes place in the reactions and behavior of these primitive and extraordinarily interesting birds.... One of the problems to be worked out in connection with the Storm Petrel is the place of the sexes in incubation." These are real challenges to an inquisitive ornithologist!

Mammals—The chief discoveries to be made in the field of Antarctic mammals would be to locate the breeding places of the Crabeater as well as the very rare Ross seals. Both species apparently breed in the pack ice, and are pelagic in their habits as compared with the Weddell Seal, whose normal habitat is the inshore waters of the Antarctic Continent and adjacent islands. Because they are pelagic, relatively little is known of their life history, particularly that of the Ross Seal.

The abundant Crabeater Seal shows every indication of being gregarious at the breeding time, but at present there is no knowledge of its whereabouts in the pack ice during breeding in early spring. *Bertram* [1940] has published an excellent treatise on this and the Weddell species and *Sapin-Jaloustre* [1952, 1953] has recently published on studies carried out by the French in Adelie Land.

Up to fifteen years ago less than fifty Ross Seals had ever been seen [*Bertram*, 1940, addendum I]. Since that time the species has been observed by several American and other expeditions. About twenty were seen in the Weddell Sea area by the recent Norwegian-British-Swedish Expedition (Ove Wilson, personal correspondence, 1956). Needless to say, any observations on populations and life-history habits of this species would be valuable contributions to our knowledge of the Pinnipedia.

Most of the permanent bases will provide opportunity for scientific collecting, and for study of breeding, growth, population dynamics, seasonal movements, and food habits of one or more of the four species of seals present in the region. Collections should be made of reproductive tracts, stomach contents, and parasites in sufficient numbers to provide good material for laboratory study. Skulls should be obtained so that age composition of the population may be determined. Better methods for aging seals also need study.

Seals should be marked by tagging or branding to determine ages and migration habits, such as was done by *Lindsey* (1937), in the Bay of Whales. As with banded birds, it is suggested that the United States Fish and Wildlife Service act as the central agency for keeping records of returns on marked seals.

With the great numbers of aircraft operating in the region during the IGY much data could be obtained by deliberate searches made over the pack ice during the breeding season. Use of a helicopter would be particularly advantageous. Aerial photographs taken at relatively low altitude, and flown in grids over the pack ice, would provide excellent basic information on distribution, populations, species composition, and age groups. Use of a type of aerial camera such as the Sonne S-7 Strip Camera could provide such detail.

Marine zoology—In many of the marine fauna groups our knowledge is still in the descriptive stage and collected materials have been from restricted areas. Little work has been done with these groups on analysis of faunal components or broad distribution [*Dell*, 1952].

Shallow-water marine zoological studies have so far been largely neglected in Antarctica. In addition to ecological studies, there is much collecting that needs to be done as a start. The relationship of the shallow-water fauna to both freezing and ice grinding is also worthy of research. Any large-scale program in marine zoology probably would not be feasible from the bases unless a ship were made available. Much valuable work could be carried out from most of the bases, however, by use of small boats, or through the ice, as was done by *Bryant* [1945] in Palmer Land.

As in the Arctic [*Dunbar*, 1955], within the Antarctic zone the phenomenon of circumpolarity appears to be fairly common, although it may well be that there are variations with circumpolar species, which will be significant of isolation within the circumpolar area, especially in the littoral and benthonic species. Collections at all the coastal bases would further our information in this respect.

General—Parasitic insects of birds and seals should be collected, and blood smears should be prepared for study of blood-borne diseases. Terrestrial insects, mites, and other forms should be collected and studied from the standpoint of their ecological and geographical relationships with respect to such factors as temperature, humidity, wind, soil or plant habitat, and other biospheric conditions.

The polar bases also offer a rare opportunity for studies of physiological responses in Antarctic animals. A matter of current interest and even controversy is the extent of metabolic regulation or compenstation with respect to temperature in poikilotherms. There is a question as to how widespread such regulation is, both geographically and systematically [*Bullock*, 1955]. Physiological studies could also include resistance of animals to extreme cold, nature of cellular 'bound-water,' and comparisons of the fat properties and the insulation of tissues in Antarctic species. Interesting work has been carried out in this field at the Arctic Research Laboratory at Point Barrow, Alaska, under auspices of the U. S. Office of Naval Research [*Irving*, 1951 and 1953]. Similar research on Antarctic animals has never been attempted. This region with its more rigorous climate and a fauna which would lend itself well to study, provides even a better field for physiological studies than the Arctic. Time would be sufficient, but qualified personnel and adequate laboratory facilities would be critical factors.

Zoological work carried out will depend on the interest and enthusiasm of a few competent people. While faunistic studies can be advanced by casual and irregular collecting and observations, real progress can be accomplished only as a result of well-planned, continued, and intensive studies.

It is proposed that a qualified zoologist be stationed in the Antarctic during the IGY. In addition to conducting research, he would correlate and direct similar work at all other American bases. This latter might be carried out by graduate students in the field of zoology, or possibly by responsible persons with keen interests in such studies, and whose other duties would permit such work.

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Botanical Research Essential to a Knowledge of Antarctica

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Abstract—Our information about the flora of Antarctica is derived largely from piecemeal collections made by members of about 20 expeditions. Their botanical work was usually limited in space and time to local areas, and represented a small fraction of their interest and effort. Above all, collections were made by scientists ill-acquainted with the type of vegetation indigenous to the Antarctic. The flora of Antarctica is preponderantly cryptogamous, and these plants besides being inconspicuous are an unfamiliar and difficult subject for most botanists. Coordinated and planned research by a trained cryptogamist is not only likely to extend the existing list of 60 mosses and some 300 lichens but is also likely to make significant strides in ecology and in intrapolar and intercontinental distributional patterns. Knowledge is also needed about the relationship of the present vegetation to ice and snow terrain and ice fluctuations. In conclusion, this research may permit ventures into the more fundamental and enigmatic problems of origin, age, and dispersal. In botany there is no substitute for the study of a natural, living population.

Introduction—Botanically, Antarctica is described as a desert, not solely because of the extreme cold and consequent dryness but also because of the physical depth and surface extent of ice fields which afford no habitats for flowering plants [*Nordenskjöld*, 1928]. In the absence of phanerogams, the cryptogams—principally the algae, mosses, and lichens—are the dominant forms of plant life. And with the exception of a few specialized groups of terrestrial algae which use snow as a substratum, the cryptogams, particularly the lichens, have been found wherever mountain peaks have breached the polar ice cap, or wherever the ice sheet has receded, exposing the low shoreline [*Mawson*, 1942]. Their abundance is relative and their size inconspicuous, but they exhibit a vigor which, in view of the severity of their environment, is frequently described as profuse. Therefore, botanical research in the Antarctic is primarily associated with the collection and study of the cryptogams.

Hooker's [1844] collection of 19 species of algae, mosses, and lichens from Cockburn Island off the Palmer Peninsula in 1843 remained for 53 years the sole proof of an antarctic vegetation south of the 64th parallel. Collections become more comprehensive only after 1900 (see Table 1), and yet the average for 16 expeditions to date is 33 species. The number of identified lichen species of East Antarctica is less than one-third of those known from the Palmer Peninsula of West Antarctica, notwithstanding the fact that 55 pct of all collections are from East Antarctica. With the exception of a few records from the mountains fronting the Ross Ice Shelf, the inland flora of the nunataks of the Polar Plateau is unknown. Historical reviews and references to the systematic, floristic and ecological problems of the cryptogams are given in *Cardot's* [1921] bryological reports, *Carlson's* [1921] publications on the fresh water algae, and the lichenological works of *Darbishire* [1910, 1912, 1923ab], *Dodge* [1938, 1948], and *Lamb* [1948a]. The special nature of these problems has not attracted general attention, even in that otherwise thorough and timely mid-century survey, *The Antarctic Today* [*Simpson*, 1952], there is no reference to the botanical aspects of contemporary Antarctic research.

The contrasting polar regions—The physical contrast between the poles may be observed in Figure 1, in which the Arctic is seen from the South Polar regions as through a transparent globe. The most striking feature of the Antarctic flora is its penury, as observed by R. W. Rudmose Brown in 1928. The statement though warranted is founded on a comparative estimate of the flowering plants. The land rim of the Arctic Basin supports over 400 species of flowering plants and the tree line extends above 70°N on the Lena. The Danish Pearyland Expedition of 1947–50 [*Troelson*, 1952] reported 90 species of vascular plants, 120 mosses, 20 liverworts, and 60 lichens from between 82° and 83°N in north Greenland. The Antarctic Continent is the only continent wholly outside the tree line, which terminates at about 53°S in Tierra del Fuego. It possesses two rare flowering plants, a grass, *Deschampsia antarctica* E. Desv. and the pink, *Colobanthus crassifolius* Hook. f., which barely exist north of the Antarctic Circle; both are thought to be recent immigrants from South America. Although the nonflowering land species of the Antarctic Continent are far

TABLE 1 – *Lichenological Collection by Expeditions to Antarctica*

Dates	Expedition and leader	Locality	Collectors	Reporting authority	Herbarium	Species
1839–43	'Erebus' & 'Terror' Exped. James Clark Ross	NE Palmer Peninsula	J. D. Hooker	*Hooker* and *Taylor* [1844]	Farlow	9
1894–95	'Antarctic'—Kristensen & Bull Exped.	Victoria Island	C. E. Borchgrevink	*Fricker* [1900]	?	1
1897–99	'Belgica'—Belgian Antarc. Exped. A. de Gerlache	Palmer Archipelago	E. Racovitza	*Vainio* [1904]	Turku	55
1898–00	'Southern Cross' Exped. C. E. Borchgrevink	Victoria Land	Hansen & Bernacchi	*Blackman* [1902] *Fries* [1902]	Brit. Mus. Uppsala	4 4(?)
1901–03	'Gauss'—German South Polar Exped. E. von Drygalski	Wilhelm II Coast	E. Vanhoeffen	*Zahlbruckner* [1906]	Berlin-Dahlem ?	3
1901–03	'Antarctic'—Swedish South Polar Exped. O.Nordenskjöld	Snow Hill and Paulet Islands (Palmer Pen.)	C. Skottsberg & J. M. Sobral	*Darbishire* [1912]	Stockholm	47
1901–04	'Discovery'—Brit. Nat. Antarc. Exped. R. F. Scott	Victoria Land	E. A. Wilson, et al	*Darbishire* [1910]	Brit. Mus.	24
1903–05	'Française'—1st French Antarc. Exped. J. B. Charcot	Palmer Archipelago	Charcot and Turquet	*Hue* [1908]	Paris	17
1907–09	'Nimrod'—1st Brit. Antarc. Exped. E. Shackleton	Victoria Land	D. Mawson and R. E. Priestley	*Darbishire* [1923a] *Dodge* [1948]	? Mo. Bot. Gard.	13 3
1908–10	'Pourquoi-Pas?'—2nd French Antarc. Exped. J. B. Charcot	W. Palmer Peninsula	Gain and Liouville	*Hue* [1915]	Paris ?	112
1910–13	'Terra Nova'—Brit. Antarc. Exped. R. F. Scott	Victoria Land	?	*Darbishire* [1923b]	Brit. Mus.	17
1911–14	'Aurora'—Australasian Antarc. Exped. D. Mawson	Geo. V Coast, Queen Mary Land	Hunter, McLean, Laseron and Harrison	*Dodge* [1948]	Mo. Bot. Gard.	69
1929–31	'Discovery'—Brit. Austr. N.Z. Antarc. Research Exped. D. Mawson	Mac-Robertson and George II Coast	Johnston	*Dodge* [1948]	Mo. Bot. Gard.	38
1933–35	'Bear of Oakland' and 'Jacob Ruppert'—2nd Byrd Antarc. Exped. R. E. Byrd	Marie Byrd and Victoria Land	Siple, Wade, Corey, Stancliff, Blackburn, Russell and Paine	*Dodge* and *Baker* [1938]	Mo. Bot. Gard.	89
1934–37	'Penola'—Brit. Graham Land Exped. J. R. Rymill	Argentine Islands S to Alexander Is. Palmer Peninsula	Fleming, Stephenson, Roberts, Bertram	*Lamb* [1939] (in part)	Brit. Mus.	?
1939–41	'Bear' and 'North Star'—U.S. Antarc. Service Exped. R. E. Byrd	Marie Byrd Land; Marguerite Bay; Melchoir Is; Alexander I Island	R. C. Fitzsimmons; Perkins, Siple, Frazier, Bailey Richardson, Bryant, Eklund	*Llano* [1950]	U.S. Nat. Herb.	7
1944–45	Falklands Islands, Dependencies Survey (Operation "Tabarin") J. W. S. Marr	Palmer Archipelago Trinity Peninsula (Palmer Peninsula)	I. Mackenzie Lamb	*Lamb* [1948abc]	Brit. Mus.	23*
1947–48	U.S.S. 'Edisto' & 'Burton Island' USN 2nd Antarc. Development Proj. (Operation "Windmill")	Knox Coast (Wilkes Land)	L. O. Smith, Lt. (jg)	*Llano* [1950]	U.S. Nat. Herb.	1
1947–48	'Wyatt Earp'—Australian Nat. Antarc. Research Exped. K. E. Oom	Mac-Robertson Coast (Enderby Land) and Adelie Coast (Wilkes Land)	A. M. Gwynn	*Dodge* and *Rudolph* [1955]	Mo. Bot. Gard.	21
1954–55	'Kista Dan'—Australian Nat. Antarc. Research Exped. R. G. Dovers	Mac-Robertson Coast (Enderby Land)	R. O. Summers and D. P. Sweetenson	*Llano* [1956]	Farlow	4

* In part.

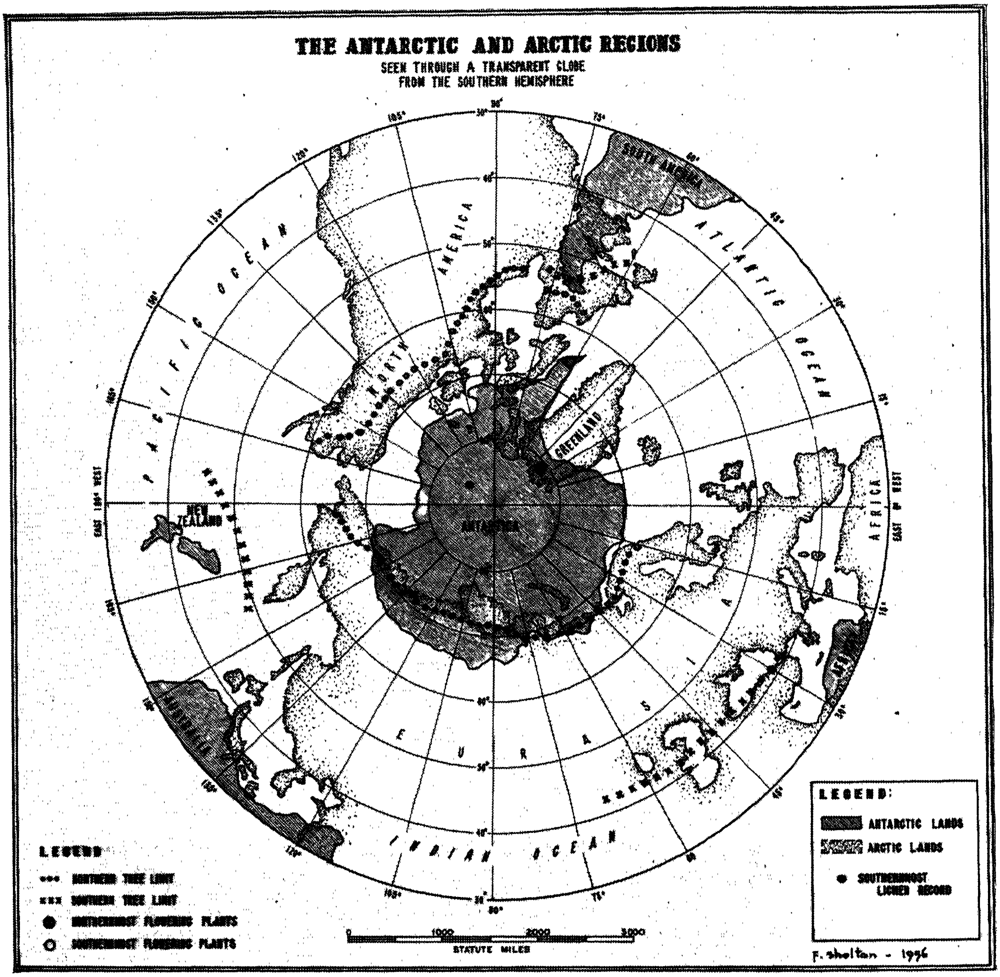

FIG. 1 – The Antarctic imposed over the Arctic

more numerous, numerically they also fall far short of the cryptogams known from the Arctic. The list consists of one fungus, six liverworts, some 60 mosses, about 200 fresh water algae, and around 400 lichen species. The probability of encountering another flowering plant is unlikely, notwithstanding the aerial finds of 'green oases' in Queen Maud Land of East Antarctica [*Ritscher*, 1947] by the German Antarctic Expedition of 1938–39, and the Bunger Oasis of Wilkes Land, discovered in 1946–47 by the Western Flight Group of the United States Navy Task Force 68 [*Siple*, 1947].

As *Brown* [1906] points out, the unfavorable factors for plant growth on the Antarctic Regions are not entirely a question of light, snow cover, or winter temperature but a consequence of "the short and inadequate summers" and "in this want of a season of growth." In brief, "while the Arctic summer mean is well above 32°F, the Antarctic summer mean is practically always below." In addition, *Brown* [1906] notes that in the lowland areas nearest South America, and most favorable for colonization by flowering plants, the great numbers and "insatiable curiosity" of penguins are "circumstances which would render plant life quite out of the question." *Skottsberg* [1905] suggested that the strong antarctic winds constitute another unfavorable condition. Although these generalizations are applied to all land plants and are given primarily as an explanation for the absence of flowering plants on the Antarctic Continent, they do not account for the presence of cryptogams.

For a more positive approach to this biologically challenging aspect of the south polar vegetation, we must refer to *Siple's* [1938] report on the ecology of the nunatak flora of Marie Byrd Land. In the

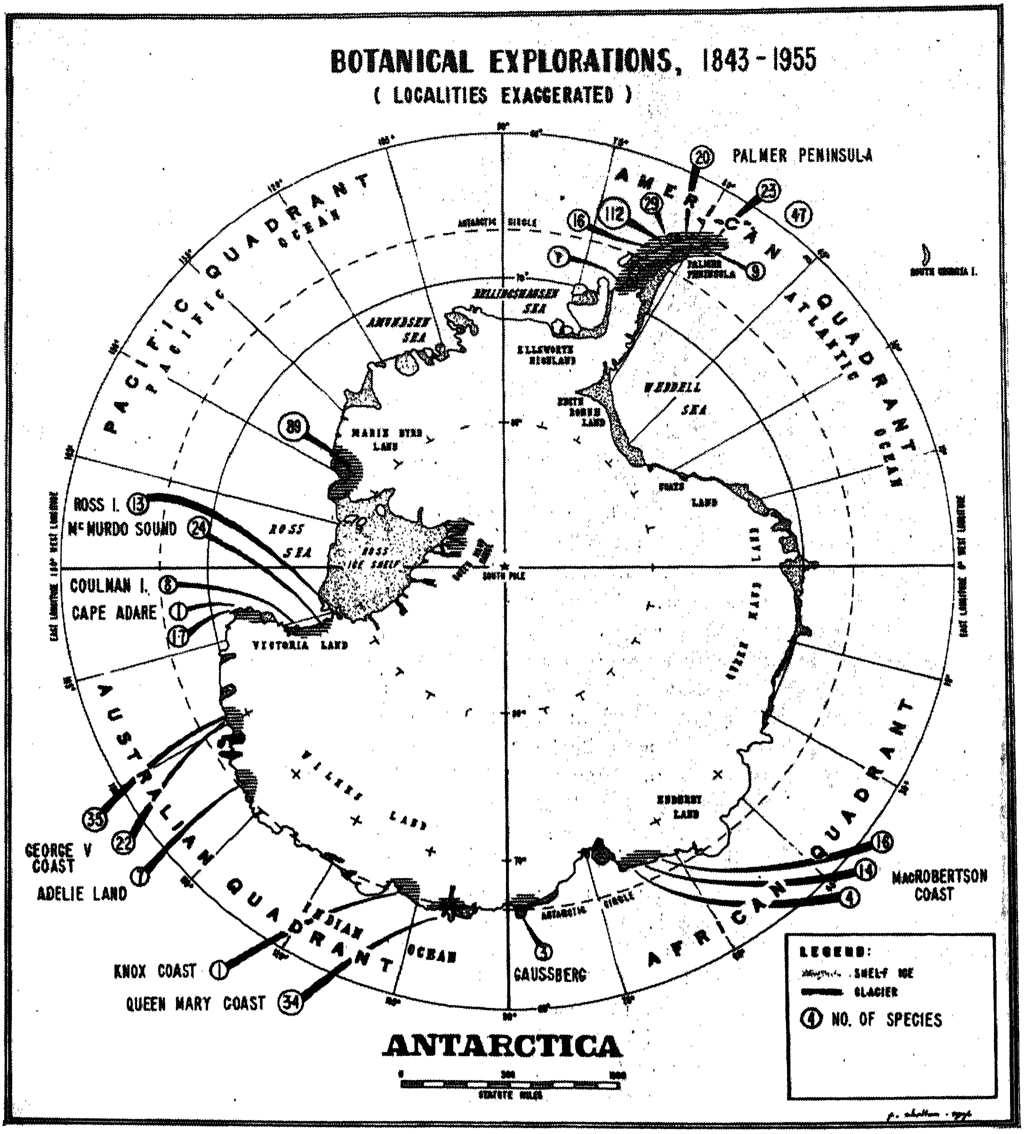

FIG. 2 – Botanical explorations in the Antarctic

matter of light and mean temperature, *Brown* [1928] and *Siple* [1938] are in general agreement but they differ markedly on plant abundance. "In some areas," Siple reports, "density of plant life was too great to obtain more than random samples . . .", and again, "the party had not been aware of the density of plant life, and consequently the supply of containers was scant." *Giaever's* [1954] account of the Norwegian-British-Swedish Antarctic Expedition in Queen Maud Land relates "that in some places the hill was bright with lichens," and "a green moss almost luxuriant in growth."

Siple's [1938] ecological contribution is pertinent in accounting for the persistency of the vegetation; he considered that wind-driven snow "must have a strong bearing upon the distribution problem of the plants" and may well be the determining factor in specific areas. This is confirmed by *Gould* [1931] who attributes the severe erosion of rocks in the Rockefeller Mountains to the abrasive force of snow blast. *Siple* [1938] further states that the nunataks have a milder climatic condition during the summer and that, at this time, the dark rocks absorb much heat. He recorded a maximum black-bulb reading of 120°F. Finally he observed that lichens were well developed near rock-nesting birds. The manuring effect of bird dung is a well-known arctic phenomenon, documented by the Swedish ecologist, *Sernander* [1912], who used the term 'nitrophilous' for species tolerating this habitat. An analogous situation exists in the Antarctic Seas, whose highly nitrated and phosphatic waters support a rich marine cryptogamous flora [*Mawson*, 1943]. This is the basis for the dynamic aspect of antarctic biology and indirectly the support of the whaling and sealing industries [*Fleming*, 1952].

The nature of lichens—The lichen marks the outer limit of land vegetation. In the Antarctic, lichens are more prolific and widespread than was previously believed. They may be expected at high altitude and latitude except where the physical violence of ice or snow is excessive, or in the event that they are buried by permanent snows. Lichens persist regardless of low temperatures—almost independent of ground nutrients and with a minimum of sunlight and moisure—longer and more completely than any other plant organism. Their persevering and chief ecological distribution factor is their ability to become desiccated and yet not die [*Scholander* and others, 1953]. The most southerly record for plants is given by Siple for eight lichen species collected between 85° and 87°S near the 150th meridian.

Lichens are an anomaly of the vegetable kingdom, distinguished by their composite nature. The combination, a fungus and an alga, so nicely balanced in unity and so widely dispersed over the Earth, must reflect a great age. Each partner is of long lineage but, unfortunately, the union is scarcely represented in the fossil record. In the absence of vascular plants lichens are a promising group for extending phytogeographical knowledge intra- and inter-Antarctic-wise [*Du Rietz*, 1929]. Our present understanding of the vegetation is, however, more or less established for the past through the paleobotanical discoveries of the fossil floras of West Antarctica [*Halle*, 1913], and the relict vascular plants of the Subantarctic Oceanic Islands [*Good*, 1947]. The latter vegetation, as *Guppy* [1919] has so aptly stated, represents "registers of past floral conditions in the continents . . . whilst their common features tell the story of the present."

The Antarctic floristic regions—Subantarctica, according to *Skottsberg* [1905], is more or less naturally divided from Antarctica along the 60th parallel, and extends north to the 45th parallel. It consists of 14 island groups to which *Good* [1947] has added the South Shetland and South Orkney Islands since, floristically, they have much in common with the Subantarctic Oceanic Islands. However, vascular plants are absent today from Bouvet Island, the South Orkney, the South Sandwich, and Balleny Islands (*Taylor*, 1954].

South Georgia, Tristan da Cunha, Gough, and the South Shetlands in the South Atlantic; Marion, the Crozets, Kerguelen, Heard, Amsterdam, St. Paul, and the Prince Edward Islands in the South Indian Ocean; and Macquarie in the Pacific possess small but unique floras which are our principal means for interpreting the floristic patterns of the Antarctic Regions. The climax vegetation is a tussock grass or inferior tundra. *Good* [1947] cites 84 species of flowering plants common to these islands. Some are of very limited distribution, many are discontinuous species, and there are others which Cheeseman characterizes as circumpolar species. The vascular flora is marked by a high degree of endemism of which 34 species of grasses and sedges have the most limited distribution. Recent phytogeographical studies of the vascular plants of New Zealand by *Cockayne* [1927], of Macquarie, Kerguelen and other oceanic islands by *Cheeseman* [1909, 1919], of the Pacific flora by *Skottsberg* [1936], and of the bipolar plants by *Du Rietz* [1940] have established the existence of New Zealand-South American-Arctic relationships which inevitably raise questions on biogeographic connections.

Although the cryptogams are more numerous, with distributional patterns which broadly substantiate the divisions and bicentric evolution of the higher plants of Subantarctica, the explanation of their distribution—when and how it took place—is no clearer. But the criterion of isolation [*Skottsberg*, 1939] with its correlated degree of endemism, which distinguishes the flora of oceanic islands from that of continental islands, applies also to the cryptogamous plants.

An example of an oceanic island is Kerguelen, which lies almost midway between South Africa and Australia and 140° east of South America. Botanists agree that its vegetation represents a very old flora. Twenty percent of the flowering plants are, according to *Cheeseman* [1919], native; of the unrestricted species, all are of South American origin and 18 have a circumpolar distribution. *Dodge's* [1948] report on the lichens states that 73 pct of the flora is endemic. The remainder are restricted to an inter-island distribution between Kerguelen, Heard, the Crozets, and Prince Edward Islands, which Dodge collectively names Kerguelia.

The continental island type is exemplified by South Georgia, which has, according to *Skottsberg* [1921], 19 flowering plants preponderantly of

Fuegian origin, suggesting a post-glacial evolution. *Cardot* [1921] found that only 41 pct of the mosses of South Georgia are endemics, and that the rest are almost equally represented in Kerguelen, Fuegia, Australia, and New Zealand. From this evidence Cardot concludes that the bryophytes are the vestige of an older antarctic flora and preglacial survivors of South Georgia. *Darbishire* [1912] determined that only 14 pct of the lichen flora is native to South Georgia and, of those having an outside distribution, he states: "Practically half . . . are common to the Arctic." The disproportionate relationship in the distribution of the vascular and nonvascular floras illustrated by these two types of subantarctic islands might be better explained in terms of the mechanics of long-distance dispersal. However, the lighter spores of lichens are usually given a better chance for wide dispersal than are the seeds of the spermatophytes.

Cardot's [1921] studies of the Antarctic mosses collected by the Swedish South Polar Expedition list 51 species, of which 47 pct are indigenous to the Antarctic Continent. The remaining 53 pct includes species extending north to some of the subantarctic islands but the majority are cosmopolitan. Cardot concludes that the Antarctic bryological flora is more boreal than Magellanic.

More recent collections [*Dixon* and *Watts*, 1918] from Queen Mary Land and Marie Byrd Land support Cardot's thesis and verify his second observation: "It is probable that the circumpolar antarctic (moss) flora is very uniform." Of the mosses collected by the Second Byrd Antarctic Expedition, *Bartram* [1938] adds: "It is not without significance that these mosses, in a broad way, are closely allied to some of the most cosmopolitan specific types. . . ."

The Antarctic lichen flora is unquestionably numerous in species and well represented in the region, but present data are from only a few, scattered coastal localities (Fig. 2). An analysis of the four most extensive collections discloses that opinions differ on the floristic relationships. *Vaino* [1904], who reported on the Belgian Antarctic Expedition specimens, and *Darbishire* [1912] who determined the Swedish South Polar collections, found that over half of the species of these expeditions are common to the Arctic Regions. *Hue* [1915], and *Dodge* and *Baker* [1938] record a predominance of endemics and describe, respectively, 81 and 94 pct of their materials as new to science.

The problems of Antarctic lichenology—Lichenologists who have determined antarctic collections have frequently had to contend with fragmentary and even more frequently with damaged specimens; these, taken by expedition members generally ill-acquainted with this type of vegetation and able to give but a small fraction of their effort to the task, are usually examples of the most obvious plants found closest to the base. Although collectors may add unwittingly to the problems of lichenologists, the principal difficulties are, however, common to the art of taxonomy. Some lichen systematists, to borrow a phrase from *Lamb* [1948a] hold too closely to an "inelastic conception of the species concept" or have failed "to allow for ecologically conditioned variation." Therefore, in the absence of decisive ecological data, presented with meager and atypical material, a worker by circumstances limited to a North Temperate environment naturally looks upon local material as the norm.

In addition, many polar lichens are sterile and lack spores which are, taxonomically, the most stable characters for determination. In the absence of spores, the less morphologically critical features of color, shape, and surface markings are used; all these criteria are subject to considerable variation. For final verification, specimens should be compared with type material. Unfortunately, one of the earliest and largest collections [*Lamb*, 1948a] has been lost, and it is necessary to depend on a literature that is not always clear.

Consequently, it is not surprising that the systematic and floristic status of antarctic lichens appears contradictory. This problem can be eased considerably by referring materials to specialists for critical reexamination and monographic treatment. Thus, *Lamb's* [1939, 1948b] critical review of the southern genus *Neuropogon* and his [1948a] equally comprehensive study of the aquatic Antarctic *Pyrenocarps*, and *Llano's* [1950] monograph of the family *Umbilicariaceae* disclose many doubtful points in the classification of these groups and, allowing for regional variations, indicate a greater uniformity in the lichen flora.

Except for *Lamb's* [1948a] ecological notes on the aquatic *Pyrenocarps* and *Siple's* [1938] observations of the nitrophilous flora of coastal nunataks, we know nothing of the principal lichen formations, the lesser associations, and the more specific communities which are common features of lichen vegetation elsewhere. Nor can we overlook the wealth of meteorological data which will accumulate during the course of the IGY inv
gations, and which will, when collated, prov
more rational approach to basic climatic f

These are inadequacies which can be re

by permitting professional and interested lichenologists the opportunity of studying the lichens in their natural environment, and thus provide a more meaningful correlation between systematic and ecological data. "Fresh, rich, well-labeled, and well-collected . . . material is desperately needed, . . . before we can make full use of the lichens in plant-geography" [*Du Rietz*, 1929].

Origin, age, and dispersal—The perplexing aspects of the origin, age, and dispersal of the flora of the Antarctic regions have resulted in a number of hypotheses for biogeographic connections which are well known, especially to the paleogeographer, who inevitably must validate the means. Let it suffice to say that the biogeographic bridges proposed by phytogeographers and by zoogeographers to accommodate their distributional patterns have not given much consideration to the presence of cryptogams in Antarctica.

Species distribution involves long-distance dispersal, a controversial subject presented in the works of *Cain* [1944], *Good* [1947], *Polunin* [1955a], and *Taylor* [1954, 1955]. The use of lichens in long-distance dispersal studies has not appealed to most botanists. "There is a rather widespread opinion among non-lichenologists that lichens are of little use to plantgeography" [*Du Rietz*, 1929], since their light spores are easily transported long distances by wind and birds. As we have noted, present knowledge does not support this theory. Moreover, the former opinion would imply a clearer conception of the Antarctic wind circulation system, a more complete understanding of the zoogeographical boundaries [*Tweedie* and *Harrison*, 1954] and paths of movement of the birds of the southern latitudes than we now possess, and a greater trust in the laws of chance. *Skottsberg* [1921] has dealt more briefly with this question: "We know little or nothing to prove such bold theories. . . ."

Obviously the solution of the problem presented by the present distribution of the Antarctic cryptogams is of interest to all phytogeographers and may allow for a more logical explanation of the relationship between the vascular and nonvascular floras of the Antarctic Regions. Aerobiological sampling of the upper air currents and of surface areas, as demonstrated by *Polunin* [1955b] in the Arctic, and core samplings of fresh snowfall areas may, when correlated with meteorological data, provide some facts worth considering. With a better understanding of the accidental and normal migratory patterns of the southern oceanic birds, we may gain more convincing information to test the probability of species distributed by long-range dispersal.

Lynge [1934] stated in his research on arctic lichens which are similar in habitat to those of the south polar regions: "If any group of plants should be able to show a persistence from (or through) glacial epochs it certainly must be the lichens." Referring back to *Cardot's* [1921] theory of the preglacial existence of the moss flora of South Georgia and taking into consideration the acclimatization and overall uniformity of the cryptogamous floras, there is the possibility that preglacial relicts may be represented by the present periglacial nunatak vegetation of the Antarctic Continent. There are several important 'if's,' at least insofar as the plants are concerned, which handicap thought in this direction. The most important is that we know little of the rapidity of even the local migrations of these plants under present polar conditions. Yet the fact remains that, although their means for dispersal are limited and subject to chance, they are sufficient to allow for their present distribution; and the present severe climatic conditions, even if we allow for casualties, can hardly be a limiting factor, at least in the number of individuals.

The theoretical significance of lichen growth—*Giaever* [1954], in the official account of the Norwegian-British-Swedish Antarctic Expedition, states: "But it was equally certain . . . that the ice had not subsided in recent decades. For here were lichens growing all the way down to the ice edge, and we knew by experience of mountain areas in Scandinavia that the establishment of lichens on areas where the ice has disappeared is a relatively slow process. There is obviously no reason to believe that lichens would spread more rapidly in a severe Antarctic climate than in a temperate climate like that of Scandinavia."

Glaciologists of late have prompted lichenologists to think about the age of individual lichens. The practical nature of such inquiries is self-evident [*Faegri*, 1933], since the information might provide a chronological measure of local ice fluctuations and a more detailed measure of historical ice recessions. The problem is basically one of individual lichen growth [*Fink*, 1917], and in the absence of factual data, estimates have varied from a few to several hundred years. *Beschel's* [1950] study of lichen mensuration, "Lichens as a determinant of age of Recent (that is, Late Glacial) moraines," was made with selected lichen species on rocks in the glacial outwashes of the Austrian Alps. By measuring and comparing the normal diameters of lichens in morainal detritus of various but establishable dates, Beschel was able to extrapolate the ages of lichens on undated moraines of the same glaciers, and of other glaciers in similar situations. The techniques involve accurate mapping of morainal features, the careful selection of species common to all areas, and the consideration of environmental influences which control the normal rate of growth but which, in excess, would affect the results of the experiment. Lichen growth is thus directly related to an abundance of water and light; elevation and decreasing temperature are not intrinsically decisive. The physical and chemical nature of the rock is an important factor, but equally important requisites for normal growth are permanent and undisturbed substrata. Thus where rocks are liable to displacement or even gradual drift, Beschel found that a lesser age is simulated. "In short," he states, "the size of lichens gives a measurement of only the length of time that their substratum has remained undisturbed and undamaged." In this experiment Beschel used crustaceous rock lichens which are known to grow slowly, and a species of *Umbilicaria*, which, as a group, are mainly found on acidic rocks.

By means of what he calls 'the lichen method' Beschel was able to ascertain that in the Hintereis and Kasselwand glaciers "individual lichens attain diameters with a calculated age of between 500 and 800 years. They therefore date back further than the first great historic glacial advance around 1600." The author concludes: "Lichens offer, because of conformity to law in their growth, other conditions being equal, a practicable means for the determination of the age of Late Glacial (including early Late-Glacial) morainal deposits."

Lichen vitality is a familiar phenomenon to the lichenologist working with herbarium material, for even the oldest specimen appears to revive when moistened. The inability to determine the end of active growth is a difficulty in measuring age. This is especially true when working with lichen species of slow growth. In addition, some lichens lose their individuality, as when adjacent species coalesce, or when the substrata partially disintegrate or, as among species which grow centrifugally, when the center of the plant disintegrates. *Beschel* [1955] concludes: "The rate of growth is directly proportional to the active annual life span and inversely proportional to the maximum age." He estimates the life span range for tropical epiphytic lichens at between one to five years in comparison to "the more than 1,000 year old" crustaceous rock lichens of the polar regions.

Conclusions—From the evidence given it is apparent that any investigation of the plants of the Antarctic Continent is the primary concern of the cryptogamic botanist. Of the three major classes of land cryptogams recorded from the region, the lichens appear to have the widest range of habitats and to provide the means for systematic, ecological and distributional studies. Their usefulness as indicators of ice fluctuations, of land relationship, and of plant dispersal methods has yet to be fully explained under antarctic conditions. To accomplish these objects successfully will require the cooperation of interested persons in allied fields of science. In addition to the lichens, every effort must be made to secure adequate collections of mosses and algae suitable for studies and in sufficient quantities for distribution to herbaria, and for exchange purposes with foreign nationals cooperating in the IGY.

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